



Final report of the roads2hycom project: fuel cells and hydrogen in a sustainable energy economy

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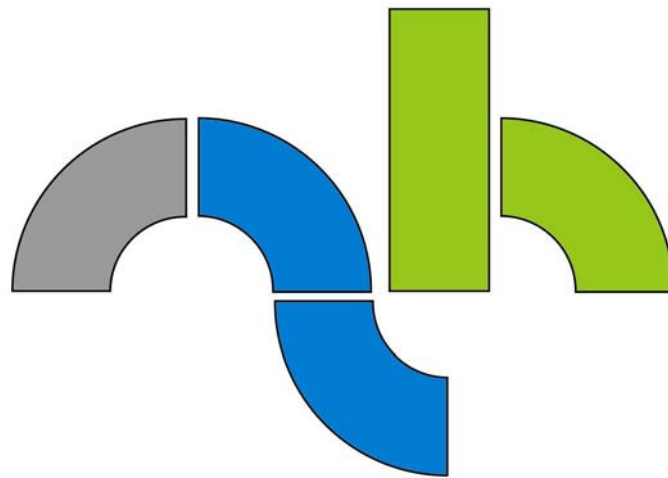
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Roads2HyCom
www.roads2hy.com

FINAL REPORT OF THE ROADS2HYCOM PROJECT

FUEL CELLS AND HYDROGEN IN A SUSTAINABLE ENERGY ECONOMY

Edited by Nick Owen, Ricardo UK Ltd
On behalf of the Roads2HyCom consortium

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The European Commission is supporting the Coordination Action "HyLights" and the Integrated Project "Roads2HyCom" in the field of Hydrogen and Fuel Cells. The two projects support the Commission in the monitoring and coordination of ongoing activities of the HFP, and provide input to the HFP for the planning and preparation of future research and demonstration activities within an integrated EU strategy.

The two projects are complementary and are working in close coordination. HyLights focuses on the preparation of the large scale demonstration for transport applications, while Roads2HyCom focuses on identifying opportunities for research activities relative to the needs of industrial stakeholders and Hydrogen Communities that could contribute to the early adoption of hydrogen as a universal energy vector.

Further information on the projects and their partners is available on the project web-sites www.roads2hy.com and www.hylights.org



DISCLAIMER

This report has been constructed from the outputs of the Roads2HyCom project. While every effort has been made to ensure the accuracy and robustness of the data presented, the authors and the project partners cannot accept liability for inaccuracy of any information presented or conclusions drawn. This report has been developed in consultation with the Roads2HyCom consortium and approved by its Core Group, but does not necessarily represent the views of individual Roads2HyCom partners.

PROJECT PARTNERSHIP



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FUEL CELLS AND HYDROGEN IN A SUSTAINABLE ENERGY ECONOMY – FINAL REPORT OF THE ROADS2HYCOM PROJECT

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1. Executive Summary

1.1 Roads2HyCom

The Roads2HyCom project is a partnership of 29 stakeholder organisations supported by the European Commission Framework Six programme. The project has studied technical and socio-economic issues associated with the use of Fuel Cells and Hydrogen in a sustainable energy economy, by combining expert studies in technology status, energy supply and socio-economics with an active programme of engagement with key stakeholders, especially early adopters of the technologies.

Over its duration, the project has provided support, information and feedback to the European Commission, the European Hydrogen and Fuel Cells Technology Platform (HFP), the New Energy World Joint Technology Initiative (NEW JTI) and the Hydrogen Regions and Municipalities Partnership (HyRaMP).

This document is the final report of the Roads2HyCom project. It summarises the key findings of over 50 reports and online information resources created by the project, all of which are available at www.roads2hy.com.

1.2 Fuel Cell and Hydrogen Technology

Emerging and disruptive technologies need to be competitive with incumbent products, in order to create niches in the market from which they can grow. Roads2HyCom has studied many aspects of the Fuel Cell and Hydrogen technology landscape, including:

- Mapping and characterisation of European technology developers
- Creation of an online State of the Art encyclopaedia which combines numeric data on key technology metrics with descriptions of recent advances
- Analysis of technical feedback from public demonstration projects, and of emerging product trends in key sectors
- Analysis and projection of the future performance of key energy chains and technology applications, enabling conditions for commercial viability to be analysed against a backdrop of rising energy and raw material prices
- Derivation of strategic recommendations for the research agenda and for training education and skills, based on the other studies above

The European technology development landscape is diverse, embracing a few large corporate players already investing at levels compatible with commercialisation, and many smaller players such as academia, institutions and technology start-ups. Ensuring that each type of organisation receives appropriate support remains a



critical issue: it is important to foster collaboration and technology exchange, but a “one size fits all” approach to financial support may not be effective.

There is evidence of significant recent progress in key issues such as the cost, durability and ambient operating envelope of the fuel cell, in both stationary and transport applications. This progress is encouraging, but there remains a need for a focused research effort, particularly in ensuring that this progress is consolidated into volume-manufactured products that are affordable and robust.

There are as yet very few fuel cell products sold on a profitable basis, but this situation is changing very fast, with forward orders for tens of thousands of units now in the domestic heat-power and telecoms power supply markets, and for hundreds of units in goods handling vehicles. These markets, together with auxiliary power and small two-wheeled vehicles, could become profitable along their value-chains in the next decade.

Road transport is the most technically challenging application, but the latest generation vehicles are realising the efficiencies that the fuel cell has always promised. Sustained research effort on cost reduction, durability and on-board hydrogen storage remains vital to realise the great economic and environmental potential in this sector.

1.3 Energy for Hydrogen as a Fuel

Hydrogen is considered an attractive energy vector because it can be derived from a number of energy sources. The project has studied critical aspects of hydrogen supply, including:

- The capacities of existing manufacture and distribution infrastructures, including online databases of these resources
- The potential of future renewable and low carbon energy resources for hydrogen manufacture
- The logistics of hydrogen transportation, electricity grid development and the use of hydrogen as a grid energy buffer
- The evolution of hydrogen energy chains in terms of costs and environmental factors

The supply of hydrogen is well established in the oil refining, chemical and metal industries; indeed, total production is not insignificant relative to the future demand for hydrogen as a fuel. Existing production methods, which are based on fossil fuels, can supply the early stages of a “hydrogen economy”, though engagement of producers is critical to ensure that production and distribution capacities remain aligned to demand.

However, to realise the full environmental credentials of the Fuel Cell / Hydrogen pairing, the supply of hydrogen fuel needs to migrate to lower carbon sources as volumes of products in use start to rise. For 2020, the project has found a lack of evidence that policy for development of renewables, carbon-capture and nuclear



power will provide an adequate energy surplus once targets for the greening of electrical power have been met; 2020 is the start of the timeframe where this issue becomes critical. High level European energy policy needs to embrace this issue robustly.

The interaction of the Hydrogen Economy with the development of the electricity grid is an important issue. The grid is moving from a centralised to a more distributed generation model due to de-regulation and the emergence of environmentally efficient smaller scale generation technologies. The synergy of hydrogen manufacture from electricity or carbon-captured fossil fuels, and its use as a grid energy buffer, needs to be considered as part of grid development strategy.

Recent major peaks in energy supply prices have rendered many previous estimates of the cost of hydrogen potentially obsolete. However, high energy prices increase the market premium for efficient energy-using devices, and the fuel cell remains one of the most efficient in many applications. The project has found that, if research targets for the capital cost of fuel cell products are met, then the supply of cost effective hydrogen fuel is likely to be feasible in the context of future energy prices.

1.4 Early Adopting Communities and Socio-Economics

Municipalities and regional authorities form an important base of early adopters, especially for high profile transportation and city power generation applications. The project has studied and engaged with this important stakeholder sector by:

- Establishing a database of existing and potential public technology demonstrations
- Characterising these early adopters in terms of their drivers and capacities, enabling conclusions to be drawn regarding key success factors
- Studying relevant European policy measures, and drawing conclusions on critical points for the future in terms of general policies and regional cluster development in Fuel Cells and Hydrogen
- Developing a set of three Handbooks for community and municipal stakeholders, which start with basic guidance on identifying whether Fuel Cells and Hydrogen is a topic of interest, and then give an overview of the technologies, planning establishing and running a project, monitoring its success, financing and exploitation

The project found that Political Will is a dominating success factor amongst these early adopters, although of course Political Will is also linked to local public perceptions, the local legacy of innovation and technology development, energy resources and social needs. The more innovative European regions and municipalities can assemble significant collective power in the purchase and deployment of Fuel Cell and Hydrogen technologies. The challenge going forward is to ensure that the complex web of European policies for transport, energy supply and efficiency, taxation, carbon trading and regional development, support this where appropriate and then allow its replication in less innovative regions.



1.5 Concluding Remarks

Fuel Cells and Hydrogen constitute a very broad topic in terms of the diversity of technological detail and socio-economic backdrop across the range of energy chains and applications. It is impossible to draw simple, universally correct conclusions, but as a generalisation it can be said that:

- The technological state of the art is advancing significantly, but the right support and incentives are required to address critical issues and realise recent progress in volume-produced applications; as well as developing the engineering, manufacturing and servicing skill-base to support their arrival in the market
- There are significant early markets created by specialised application niches and by the political will of municipal early adopters; these markets need to be encouraged to grow and replicate by implementing appropriate policy, in a manner that is stable long-term, at European level
- There is a critical need to link the development of sustainable and low carbon energy policy, to that for the supply of Hydrogen as a fuel, so that the environmental potential of hydrogen-fuelled applications can be realised. The linkage to grid development and sustainable electricity (which both complements and competes with hydrogen as an energy vector) is especially critical

The challenge now for Europe is to bring together critical masses of stakeholders in technology development, energy supply and the wider community in order to ensure that the vision of Fuel Cells and Hydrogen in a sustainable energy economy is realised. The project has developed seven “success factors” for this to happen:

| Roads2HyCom’s seven success factors for Fuel Cells and Hydrogen in a Sustainable Energy Economy | |
|---|--|
| Vigorous research to address key issues | – Realisation of mass-production, durability and impurity tolerance, Hydrogen storage in vehicles |
| Development of the Skill-base | – Research, product engineering, manufacturing, servicing |
| Stimulation of early markets | – Fiscal incentives, Civic procurement, removal of bureaucratic barriers, sharing of learning |
| Financing | – Availability of research and infrastructure grants, venture capital and business loans, on a suitable, stable and secure basis |
| Stability of long term policy | – Sustained policy support, financing and incentives to promote industrial investment in mass production |
| Joined-up Energy Policy | – Clarity of priorities (environment, energy security), Availability of low-carbon energy, integration with a smarter electricity grid |
| Flexible European Cohesion | – Playing to our strengths in international markets |



2. Background – Fuel Cells and Hydrogen in Europe

The transformation to a global sustainable economy will be the greatest feat of technological and socio-economic engineering ever undertaken. It will require unprecedented levels of international collaboration; forward planning and investment well beyond the horizons of normal commercial enterprise; and sustained, focused research and technology development (RTD) effort to advance the capabilities of today's sustainable energy technologies to the point where they are compatible with commercialisation in a future global market.

The broad long-term policy of Europe, and many of the world's other major economic powers, is for a sustainable or zero carbon energy supply based on energy distribution in the form of Electricity and Hydrogen. Electricity has an existing infrastructure (although it will of course require reinforcement) and is a familiar energy vector in many applications; Hydrogen offers the advantage that it can be produced from many primary energy sources (including fossil fuels, bio-mass, renewable and nuclear energy), and produces no carbon dioxide and typically low levels of other pollutants at the point of use. The conventional assumption (which is generally but not universally applicable) is that electricity will be used more for stationary applications (which can be grid connected), while hydrogen (which can store energy more densely than an electric battery today) will be the energy vector for mobile or remote applications. Other energy vectors, such as liquid bio-fuels, may also compete in the same arena, especially in the medium term.

The Fuel Cell is an energy conversion device that converts its fuel (usually hydrogen or a hydrocarbon like natural gas) into electrical energy, with higher efficiency than many technologies in use today. Because most fuel cell types can or must use hydrogen, the two technologies are often linked, although it is perfectly possible to adopt one without the other.

The European Strategic Energy Technology plan (SET-Plan), published in November 2007 [2.1], cites a broad range of challenges for achieving the Commission's visions for the years 2020 and 2050, covering the whole energy spectrum from nuclear and carbon-captured fossil fuels to bio-fuels, renewable energy, and energy efficiency. Among these challenges are

- “Bring to mass market more efficient energy conversion and end-use devices and systems in buildings, transport and industry, such as poly-generation and fuel cells” (to contribute to targets for 2020), and
- “Develop the technologies and create the conditions to enable industry to commercialise hydrogen fuel cell vehicles” (to contribute toward vision for 2050)

A range of measures will be required to stimulate the arrival of hydrogen as a commercially viable energy vector, and the fuel cell as a power-plant. These may include fundamental and applied research, demonstration or pilot programmes with a



selected technology, development of infrastructures, training and education of personnel. The SET-Plan cites the importance of co-operation between governments and industrial stakeholders from regional to international levels. In many cases it may be appropriate to focus and integrate these activities via early-adopter “Hydrogen Communities”. In Europe such activity will require appropriate financing mechanisms under future Framework programmes.

Key points from the European Commission’s SET-Plan, November 2007

Key EU technology challenges for the next 10 years to meet the 2020 targets:

- Make second generation bio-fuels competitive alternatives to fossil fuels, while respecting the sustainability of their production
- Enable commercial use of technologies for CO₂ capture, transport and storage through demonstration at industrial scale, including whole system efficiency and advanced research
- Double the power generation capacity of the largest wind turbines, with off-shore wind as the lead application
- Demonstrate commercial readiness of large-scale Photovoltaic (PV) and Concentrated Solar Power
- Enable a single, smart European electricity grid able to accommodate the massive integration of renewable and decentralised energy sources
- Bring to mass market more efficient energy conversion and end-use devices and systems, in buildings, transport and industry, such as poly-generation and **fuel cells**
- Maintain competitiveness in fission technologies, together with long-term waste management solutions

Key EU technology challenges for the next 10 years to meet the 2050 vision:

- Bring the next generation of renewable energy technologies to market competitiveness
- Achieve a breakthrough in the cost-efficiency of energy storage technologies
- Develop the technologies and create the conditions to enable industry to commercialise **hydrogen fuel cell vehicles**;
- Complete the preparations for the demonstration of a new generation (Gen-IV) of fission reactors for increased sustainability;
- Complete the construction of the ITER fusion facility and ensure early industry participation in the preparation of demonstration actions
- Elaborate alternative visions and transition strategies towards the development of the Trans-European energy networks and other systems necessary to support the low carbon economy of the future
- Achieve breakthroughs in enabling research for energy efficiency: e.g. materials, nanoscience, information and communication technologies, bio-science and computation



In 2004, the European Commission proposed two public funding initiatives to kick-start the “Hydrogen Economy” [2.2]. The integrated activity of research, infrastructure development and early adopter promotion was described as “HyCom”, while the “HyPoGen” initiative focused on developing fossil-fuelled power stations with carbon capture technology, producing both carbon-free electricity and carbon-free Hydrogen, the latter being, in principle, used to support the “HyCom” initiative.

Since that time, the SET-Plan has effectively superseded “HyPoGen” and the “HyCom” concept has evolved into the “Joint Technology Initiative for Fuel Cells and Hydrogen”, a public-private partnership that combines research and enlarged demonstration activities [2.3]. The latter are, potentially, the seeds of yet larger “Hydrogen Communities” in the future. The JTI is supported jointly by industry and by the European Commission through the Seventh Framework programme (FP7), with potential for extension using National and Regional funding schemes in a similar manner. Initial preparatory planning for this JTI has been conducted by the Commission and by the European Technology Platform for Hydrogen and Fuel Cells (the HFP), a stakeholder body created as a conduit to the Commission [2.4].



3. The Roads2HyCom project

3.1 About the Project

Roads2HyCom (“Research co-Ordination, Assessment, Deployment and Support to HyCOM”, and often further abbreviated as “R2H”) is an Integrated Project supported by the European Commission’s Framework Programme Six (FP6), Priority 6.1 “Sustainable Development, Global Change and Ecosystems”. It is a techno-socio-economic research project acting as a planning support and stakeholder outreach instrument for the European Commission and the Joint Technology Initiative.

Roads2HyCom Project Objectives

The over-riding objective of Roads2HyCom is to assess and monitor current and future Hydrogen and Fuel Cell technologies for stationary and mobile energy generation against current and future application requirements, and the needs of communities which may adopt these technologies, in order to support the Commission and stakeholders, particularly the HFP, in planning future activities. In detail, this objective can be sub-divided to align with the project work-package structure:

- To create a methodology to link the assessment of RTD, the availability of Hydrogen resources, and the profile of candidate Hydrogen Communities. This methodology will form the basis of the project. Hydrogen Communities refers to early adopters of Hydrogen and Fuel Cell technologies, having the potential to lead to coordinated, larger-scale adoption of such technologies within a coherent end-user grouping
- To monitor and map European RTD into hydrogen and fuel cell technologies, and assess the current State of the Art in each, and map at overview level comparable activities in the rest of the world. These technologies embrace production, distribution, storage and conversion of hydrogen as an energy vector
- To map existing and potential future hydrogen resources and infrastructure, including industrially manufactured hydrogen, renewable and low carbon energy resources, existing and potential future distribution networks
- To map existing and potential Hydrogen Communities, and categorise them with generic profiles that can be related to future uptake of Hydrogen and Fuel Cell technologies
- To identify evolutionary pathways by which current mainstream technologies in each sector can evolve or be implemented in a commercially and technically feasible manner, towards the needs of a sustainable long-term future, beyond the HFP vision for “Snapshot 2020”
- To identify gaps and opportunities in technologies and infrastructure, and related economic issues, on the basis of the current and predicted future state of the art, current and future energy resource profiles of Hydrogen Communities, Evolutionary pathways for mainstream usage, Human and financial resource limitations, Political / policy drivers and Lessons learned from ongoing projects



- To support the introduction of Hydrogen and Fuel Cell energy technologies in R&D agendas at researcher, industrial, regional, national and commission levels. This support is based on technical and socio-economic analysis, engaging stakeholders, and includes provision of information access tools
- To provide support to the European Commission and its Hydrogen and Fuel Cells Technology Platform by: Providing feedback on documents produced by the Hydrogen and Fuel Cell Technology Platform during the lifetime of the project, using factual project data wherever possible; Supporting Commission events such as forums of researchers, regions or other stakeholders; Supporting specific requests from the Commission for information, support to meetings or workshops etc
- To contribute to the engagement and planning of “Hydrogen Communities”, via: Information exchange with stakeholders and relevant EU projects such as HyLights; Engagement of potential communities and further stakeholders in planning activity, training and dissemination and gaining feedback from respective communities; Creation of a “Hydrogen Communities Handbook” to guide planning and to attract further communities (which embraces technology choice, socio-economics, logistics, risk, safety and regulation aspects, and information on financial incentives for business development, and Public Private Partnerships)
- To promote understanding of Hydrogen and Fuel Cell technologies, “Hydrogen Communities”, and the Hydrogen Economy, by: Bringing together diverse areas of partner expertise in the project itself; Engagement of non-partner stakeholders in project workshops; Dissemination and training activity aimed at expert, semi-expert and marginal stakeholders; Provision of project reports, data, and information access / decision guidance tools on a website

In practise, what the project does is to bring together detail studies on the landscape and state-of-the art in critical technologies, infrastructure and resources for future energy supply (especially in the form of Hydrogen), and the characteristics and needs of early-adopting communities (including political drivers and financing issues), to examine the process of transition from the present day to a future where both Fuel Cells and Hydrogen play significant roles in the energy economy. The project has delivered detailed reports on each topic along the way, supported by online databases and knowledge resources; it has also delivered stakeholder workshops aimed both at technologists and those active in establishing politically-motivated early adopter communities.

Further information, and all the detailed reports and databases referred to in this document, are available at the project's website www.roads2hy.com.

The project has the European Commission DG-Research reference number SES6-019723.



3.2 Project Methodology and Structure

The project is structured around eight work-packages, of which WP 1 to 7 forms the functional core (WP5 was merged into WP4 during an early re-structure of the project).

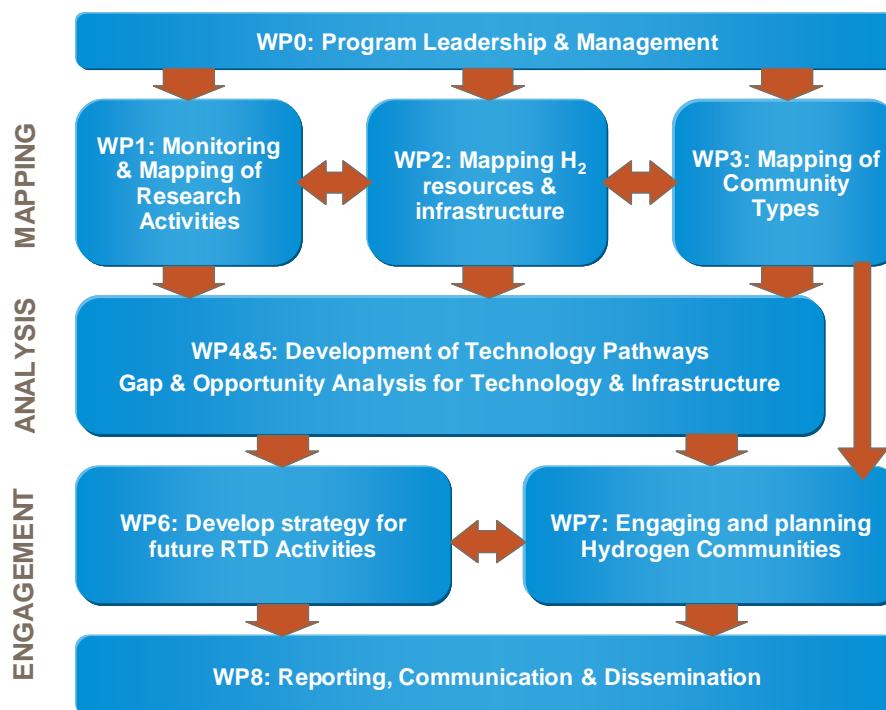


Figure 3.1: Roads2HyCom Project Structure

WP1, 2 and 3 essentially gather information, supported by some initial analysis. In WP4, this information is further analysed to look at how technology development, resources and infrastructure, and early-adopting communities, can come together to promote evolutionary steps in the energy economy. WP6 and 7 are the project's outputs, with WP6 being directed towards technologists and WP7 towards community stakeholders.

Linking so many fields in a totally objective and relevant way is a very great challenge. Mathematically based techniques were considered but rejected on the basis that the number of arbitrary factors (weightings, rankings, interactions) involved would render any result unreliable. Instead, the project devised a framework of "metrics" which were available to be considered, where relevant, by each work-package and task. This basic framework served to ensure that important issues were considered through the project, but allowed the development of detail sub-methodologies (including in some cases detailed sub-metrics) for each task. Of course some of these metrics are not relevant to some parts of the study, in which case they were disregarded.



Table 3.1: Roads2HyCom Metrics

| Metrics | Example Definition |
|-----------------------------|---|
| Technology Accessibility | Product availability, IP restrictions |
| Global Environmental Impact | Life-cycle CO ₂ or resource use |
| Local Environmental Impact | Impact on local air quality, noise, etc. |
| Efficiency | Efficiency of system relative to benchmarks |
| Capacity & Availability | Percent up-time of a system, capacity of infrastructure |
| Cost | Purchase, operation, life-cycle costs |
| Safety | Safety in use relative to benchmarks |
| Public Acceptance | Public attitude toward technology / infrastructure |
| Political Will | Availability of funding, enabling legislation |
| Security and Sustainability | Energy chain security or sustainability |
| Potential for Growth | Ability to reproduce application in another area |

Further description of these metrics, and how they were used in the gathering and analysis of data for the project, is given in the following sections of this report.



3.3 The Project Partnership

The project has been executed by a consortium of 29 partners from industry, consultancies, research institutions and academia, representing sectors such as Energy and Hydrogen supply, Transport industries (surface and air), Stationary power (buildings, industry), Engineering and Socio-Economic research, and Community expertise. Every partner has had an active role in the project (beyond a simple advisory capacity), with the objective of ensuring that information used had the benefit of input and peer review from the broadest possible cross-section of sectors.



Figure 3.2: Roads2HyCom Consortium

The project has enjoyed the financial support and guidance of the European Commission, DG-Research. As such, it has sought to work alongside related Commission-supported projects and initiatives, including:



HYLIGHTS

- HyLights is a co-ordination action to accelerate the commercialisation of hydrogen and fuel cells in the field of transport in Europe. The two projects have co-operated in a number of areas including exchange of information on Hydrogen infrastructures and Demonstration projects; and the organisation of Workshops [3.2]



- **HyWays** is a research project which has developed roadmaps and market transformation models for the development of a Hydrogen economy; scenarios and information from this project has been used as a basis for parts of Roads2HyCom [3.3]



- **Dynamis** is a project to prepare the ground for large-scale European facilities producing hydrogen and electricity from fossil fuels with CO₂ capture and permanent storage. Roads2HyCom has held joint workshops with Dynamis and exchanged information on CCS [3.4]



- **HFPEurope** – the European Hydrogen and Fuel Cell Technology Platform (HFP) is a stakeholder body, which facilitates and accelerates the development and deployment of cost-competitive, world class European hydrogen and fuel cell based energy systems and component technologies for applications in transport, stationary and portable power. Roads2HyCom has supplied feedback on two drafts of the HFP's "Implementation Plan", a foundation document for the JTI described below; Roads2HyCom partners have served on several of the HFP's working groups and employed project information in that role [3.5]



- **JTI** - Branded as "New Energy World" and officially titled the Fuel Cells and Hydrogen Joint Technology Initiative, the JTI is a public-private partnership on an unprecedented scale, with the objective of bringing these technologies closer to commercialisation [3.6]. Roads2HyCom has supplied detail recommendations into the planning of JTI activities



- **HyRaMP** – the European Hydrogen Regions and Municipalities Partnership is a partnership of potential municipal early adopters of Fuel Cell and Hydrogen technologies. Roads2HyCom supported the foundation of HyRamp, and has organised workshops in collaboration with them [3.7]



4. The Technology Landscape

4.1 Why the Technology matters – And how the project studied it

In order for any Fuel Cell or Hydrogen based product to be attractive, it has to perform competitively against the alternatives. Simply put, this means offering comparable functionality and reliability, at a price that is attractive relative to any fiscal incentives that may (or may not) be in place to promote uptake of the new technologies for environmental reasons. The competing conventional technologies – the internal combustion engine, the gas turbine, and the heating boiler – are all very mature, with the benefit of a massive worldwide service and supply infrastructure. Therefore it is vital that the research and technology arena delivers solutions that are highly functional, efficient and robust.

What are the key technologies?

The Fuel Cell is an electro-chemical device that turns a fuel (often Hydrogen or Natural Gas, but other fuels are feasible) into Electricity. In a simple sense it can be considered as being like a battery that is re-fuelled. In static applications the Fuel Cell is used directly to create electricity (and often also heat) for general use; in Transport it is used to drive the vehicle or vessel with an electric motor. Key systems are:

- The Fuel Cell stack itself – key issues often being durability, size, operation in extremes of heat and cold, and ability to manufacture it cheaply
- The “balance of plant” – air compressors, fuel reformers (to turn other fuels into Hydrogen), pumps and cooling systems - generally known technologies that need significant adaptation to this purpose
- Electrical systems – including electronics for power control, batteries and motors, are all important, especially in transport, and tend to be costly today
- The Hydrogen tank – Hydrogen is a challenging fuel to store, and all the known methods tend to be bulky and costly

Hydrogen is a carbon-free fuel that can power a Fuel Cell or more conventional devices. Key challenges for making it available as a fuel include:

- Improving Production methods to be more efficient, sustainable and cost-effective
- Improving Distribution technologies so that infrastructure investments yield a better return
- Addressing Safety issues so that the fuel is welcomed by users



Therefore it is important to understand the landscape of Fuel Cell and Hydrogen technology today, both in terms of the technology itself and the way it is being developed, implemented and received by its users. To this end, Roads2HyCom conducted the following studies:

- A study of the landscape of research and technology development organisations in Europe, based on the largest online survey of its kind ever undertaken
- A study of the technical State of the Art, based on an extensive literature search and dialogue with ongoing projects
- Studies of technical and socio-economic issues affecting uptake, including Safety, Public Acceptance, the extent of Political Will and direct experiences from recent Demonstration projects

4.2 Political Will for Hydrogen and Fuel Cell Technology

4.2.1 Political support for research via Public Funding

As with any set of technologies that are not yet ready for commercialisation, political will is important in terms of support for basic and applied research, public demonstration and creating conditions that are conducive to market uptake. Any challenging new technology needs such support to enable development. This support can occur through both political will and public acceptance.

The project studied political will for Fuel Cell and Hydrogen technology by looking at public research and development spending in comparison to spending on other competing or complementary technologies [4.1]. The global public expenditures on hydrogen and fuel cells are estimated at approximately \$1040 mil (€833 mil) per year (2003-2005); of which 30% is by Japan, 32% by the EU-25, 24% by the USA, and 14% in the rest of the world. Taking into account the larger population of the EU, the EU trails the United States and Japan in per-capita R&D expenditures, a factor which could create disadvantage as the technology approaches commercialisation. Another relevant factor is that public research funding in the EU-25 (or now EU-27) is divided between European Framework, National and Regional programmes, and despite many efforts the trans-national linkage of the latter is not always effective [4.2]. Despite this, Germany Italy and the UK rank above Canada in Fuel Cell and Hydrogen public research expenditure, as shown in Table 4.1.

Table 4.1: Ranking of countries by R&D topic [4.1]

| | H ₂ & fuel cells | Biomass | Photovoltaics | Wind | Nuclear |
|----|-----------------------------|-------------|---------------|-------------|-------------|
| 1. | Japan | USA | Japan | USA | Japan |
| 2. | USA | Japan | USA | Germany | France |
| 3. | Germany | Netherlands | Germany | Japan | USA |
| 4. | Italy | Sweden | Netherlands | Netherlands | Germany |
| 5. | UK | Canada | Italy | Denmark | Italy |
| 6. | Canada | Germany | Switzerland | Spain | Canada |
| 7. | France | Finland | Spain/France | Sweden/UK | Switzerland |



Figure 4.1 shows research and development expenditure for a series of technologies monitored by the IEA [4.1]. Although it is hard to reach a robust conclusion because of a lack of historic data, there is evidence of a significant increase in public funding for Fuel Cell and Hydrogen technologies in the past decade, and the technology appears well supported relative to other clean energy sectors.

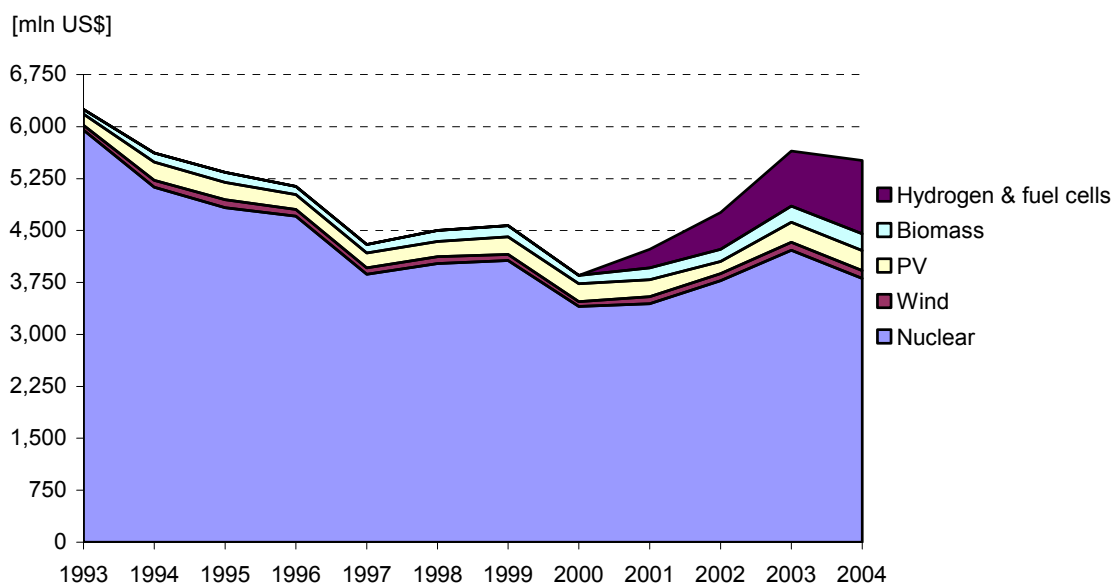


Figure 4.1: RD&D expenditures for nuclear, PV and biomass (and H₂ & FC) [4.1]

Note: The 'wedge' for H₂ & FC is indicative of lack of historical data for this category of R&D.

4.2.2 Public Acceptance

Public acceptance is of great importance for introducing a new technology into the market. Even if the technical bottlenecks have been solved, the public still needs to be convinced of the advantages of an upcoming new product. The project did not conduct its own acceptance analysis, but conducted an extensive review of other studies [4.3] and of feedback from existing demonstration projects [4.4, 4.5]. Evidence gathered indicates reasonable acceptance of Fuel Cell and Hydrogen technologies, especially when compared to other advanced or emerging fields such as Nuclear power or Genetic engineering. Of course it is important to recognise that acceptance of a carefully managed demonstration (even one with direct public contact such as hydrogen-fuelled buses) is a different matter to acceptance of an individually purchased product, and that any game-changing technology can be expected to suffer un-anticipated issues in early applications; however in terms of general acceptability, evidence suggests that a Fuel Cell / Hydrogen product with suitable attributes would be accepted.

A significant public acceptance issue with Fuel Cells and Hydrogen is safety, particularly in relation to Hydrogen as a fuel. The public would be most exposed to



hydrogen through road vehicles and their refuelling stations. Therefore, it is vital to find out how the public currently perceives hydrogen, and what feedback could be given and how the engagement of the broader public might be increased.

Surveys were undertaken in the US relating to Daimler fuel cell vehicles [4.4], and Figure 4.2 indicates that a majority of the sampled users feel safe in driving vehicles using Fuel Cell technology with hydrogen as the source of fuel. However, such perceptions can alter with media exposure to incidents, so the project undertook a review of safety assessment methods, safety issues and regulations [4.6]. Hydrogen has been used safely in industrial applications for over a century, meaning that the key risks such as leakage, combustion / detonation and hydrogen embrittlement are well known. More specific risks related to new technologies like the Fuel Cell stack or lightweight on-board hydrogen tank are less resolved (for example thermo-mechanical failure), but the exhaustive product validation and testing processes used in the automotive industry can be adapted to address these risks.

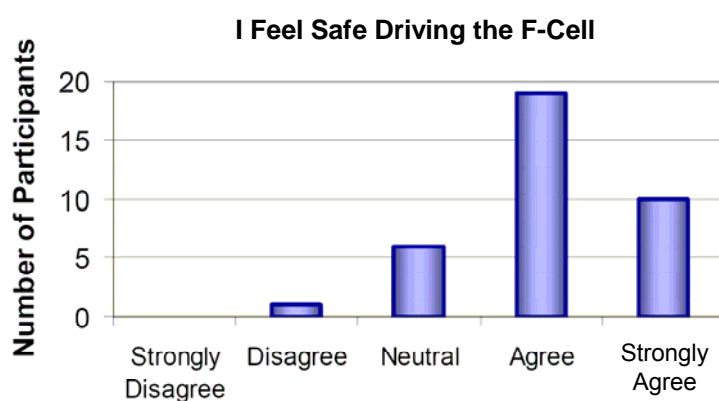


Figure 4.2: Customer acceptance and perception study results [4.4]

The safety study also mapped 67 different existing and draft European and international standards relating to Fuel Cell and Hydrogen applications. This is (and needs to be) an area of significant current progress, but a key challenge will be educating technologists in the application of such a large number of standards.

In conclusion, public acceptance of Fuel Cell and Hydrogen appears to be good relative to the timeline for introducing the technology. Safety issues are addressable, and much work has already been done to ensure the safety of the systems. But political drive is still required to put a useable framework of standards in place for products and their use, including ensuring implementation is not obstructed by misinformed concern at local level.



4.3 The Landscape of Fuel Cell and Hydrogen research in Europe

Before looking at the achievements of the technologies themselves, it is useful to understand the context in which they are being developed. Roads2HyCom has developed a map of “who is doing what” in European technology development, by collating data through an online questionnaire [4.7]. The questionnaire posed a series of questions ranging from information on the organisation and its areas of research through to funding mechanisms for the R&D. Over 400 questionnaire entries were received, from a target list of over 1200 potential organisations including both industry and academia. Validity of the data set was monitored by looking for stabilisation of key trends as the data set increased.

The results of the data analysis showed that **most of the developed economies in Europe have significant players in the field**. Germany and UK dominate with the greatest number of responding organisations (44% of the questionnaire entries were from Germany or UK). Figure 4.3 and Figure 4.4 show the geographical split of questionnaire responses.

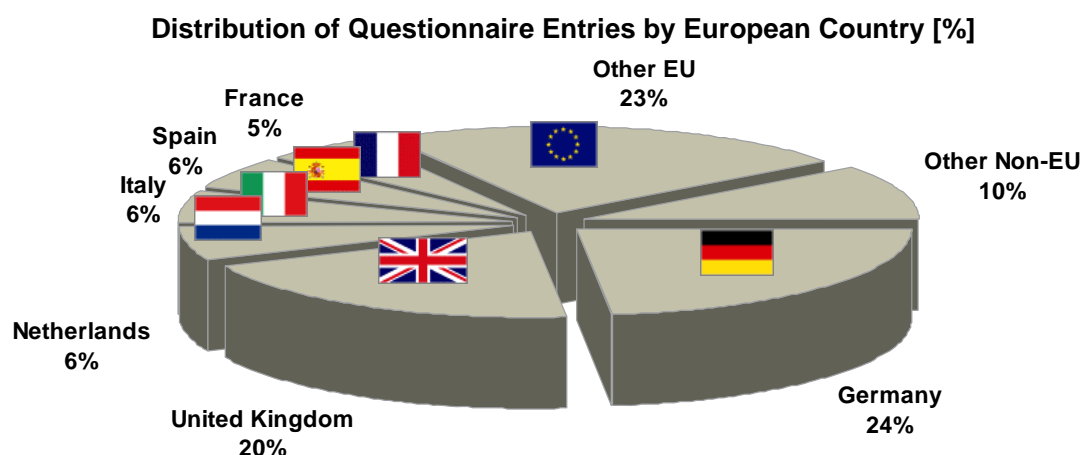


Figure 4.3: Distribution of Researchers Questionnaire entries by EU country [4.7]

The data set consists of 346 questionnaire entries from within Europe, 310 within the EU-27; 36 within Europe, but outside of the EU-27.

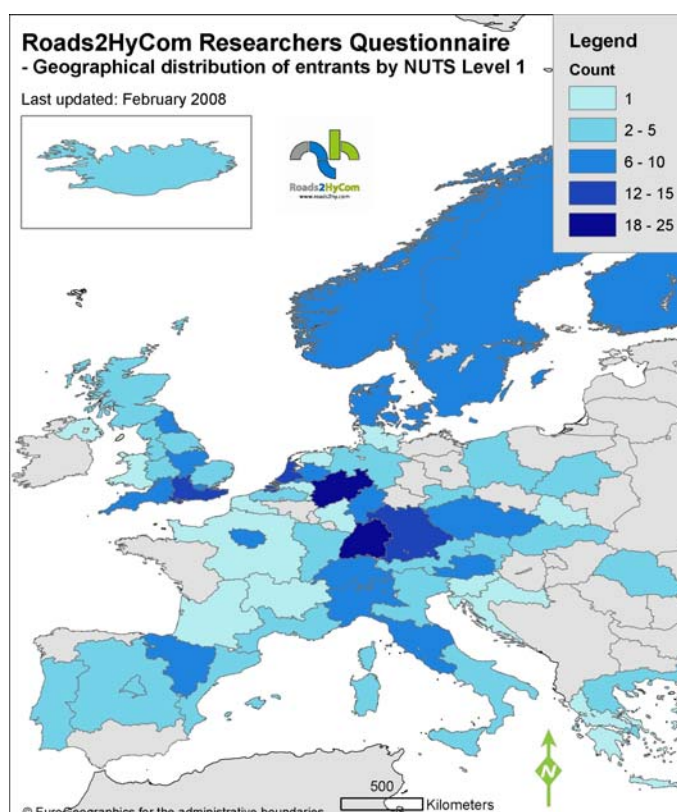


Figure 4.4: Distribution of Researchers Questionnaire entries by EU region

The European technology landscape contains a surprisingly large number of players. This mix ranged from universities and research laboratories to small independent companies and large corporate organisations. There was a polarisation in organisation size, with most tending to be small (< 50 employees) or very large (> 1000 employees). Implied in this statistic is that future political support frameworks need to encourage linkage between the small, innovative but often poorly financed players and large organisations with greater financial stability.

The financial data (Figure 4.5) indicates a majority of organisations spending too little on technology development to achieve significant product commercialisation. Depending on market, development of a product capable of significant market share typically requires a technology development spend of €100m - €1bn, spread over 5-10 years leading up to launch; a small but significant number of players fall into this category. Those that did were a mix of corporate (meaning that they have an existing business to which Fuel Cell and Hydrogen can be added) or Independent (meaning that they are focusing on Fuel Cell and Hydrogen technologies) commercial organisations, acting either as the manufacturer or supplier of a key system.

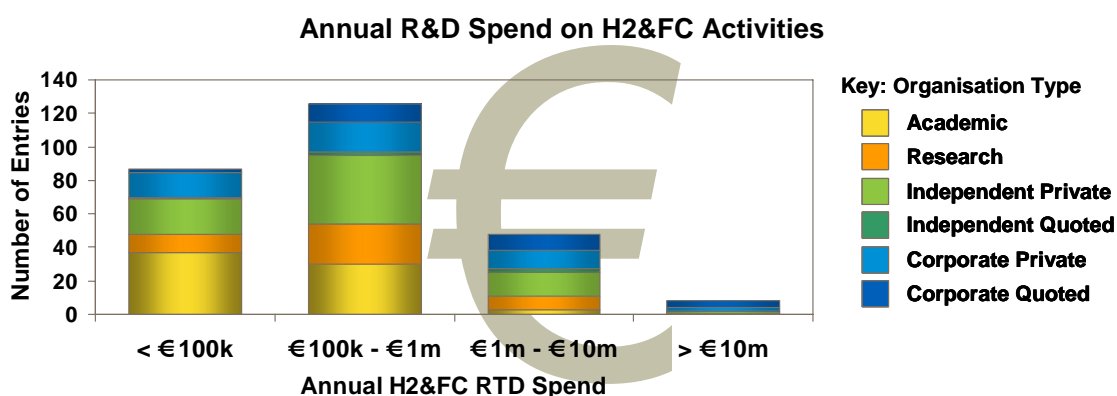


Figure 4.5: Research and Technology Development spend [4.7]
269 out of 323 entries provided information on Annual Spend

| | | <i>Financial contribution to an organisation's H₂&FC RTD</i> | | | |
|--------------------|------------------------------|---|---------|---------|------|
| | | 10%-30% | 40%-60% | 70%-90% | 100% |
| External Funding | Bank Loans | 3% | 0% | 0% | 0% |
| | External Other | 6% | 4% | 2% | 2% |
| | Company Budget | 12% | 17% | 12% | 8% |
| Internal Funding | Academic Funding | 12% | 5% | 2% | 2% |
| | Venture Capital | 3% | 1% | 2% | 0% |
| | Third-Party Private Investor | 5% | 2% | 0% | 0% |
| | Personal | 4% | 2% | 0% | 1% |
| | Internal Other | 3% | 1% | 1% | 0% |
| Grants & Subsidies | Regional R&D | 17% | 1% | 1% | 0% |
| | National R&D | 30% | 14% | 6% | 6% |
| | EU (Framework) R&D | 26% | 13% | 3% | 4% |
| | Subsidy Other | 4% | 1% | 0% | 1% |

Figure 4.6: Percentage of entries receiving funding by contribution for each Financial Resource option [4.7]
224 out of 323 entries provided information on Financial Resources



83% of entrants that supplied information about their financial resources claimed at least one grant or subsidy to support their activity; grants rank alongside corporate finances as dominant funding sources. As such grants usually exclude support to commercial development, it can be again inferred that a majority are essentially still pre-commercialisation and dependent on support from European, national and regional governments. Figure 4.6 shows the distribution of funding sources for FC&H2 R&D.

The technical focus of Fuel Cell and Hydrogen research was shown to be diverse. Although most was focused on producing marketable products, there are also researchers investigating other aspects of using FC&H2 technology, such as socio-economics, government policy, health and safety, regulations and standards. Most questionnaire entrants were working on more than one aspect of the technology (though the dominance of grant funding suggests that this may be achieved via collaboration). Stationary applications (58% of respondents) are nearly as popular as transport applications (65%); the fuel cell itself being the most popular technology at 63%. However, production, distribution, storage and usage all feature in the responses.

4.4 State of the Art in H2&FC Technology

Understanding the current state of the art (SOTA) in FC&H2 technology is critical to determine how far the technology is away from potential commercialisation, and the technological gains needed to get it there. Roads2HyCom has developed an interactive tool to which uses a “Wiki” structure [4.8] to collect project expert input and present the state of the art in FC&H2 technology, and present it in an online encyclopaedia [4.9]. Input was collected from project partners and a number of contemporary research projects. The encyclopaedia is structured according to a “technology tree” (Figure 4.7), which divides technologies by their place in the energy chain and type of application, then breaks down further to system level. For each technology area, descriptive text on important issues is accompanied by data in the categories of the Roads2HyCom “metrics” described in Chapter 3.

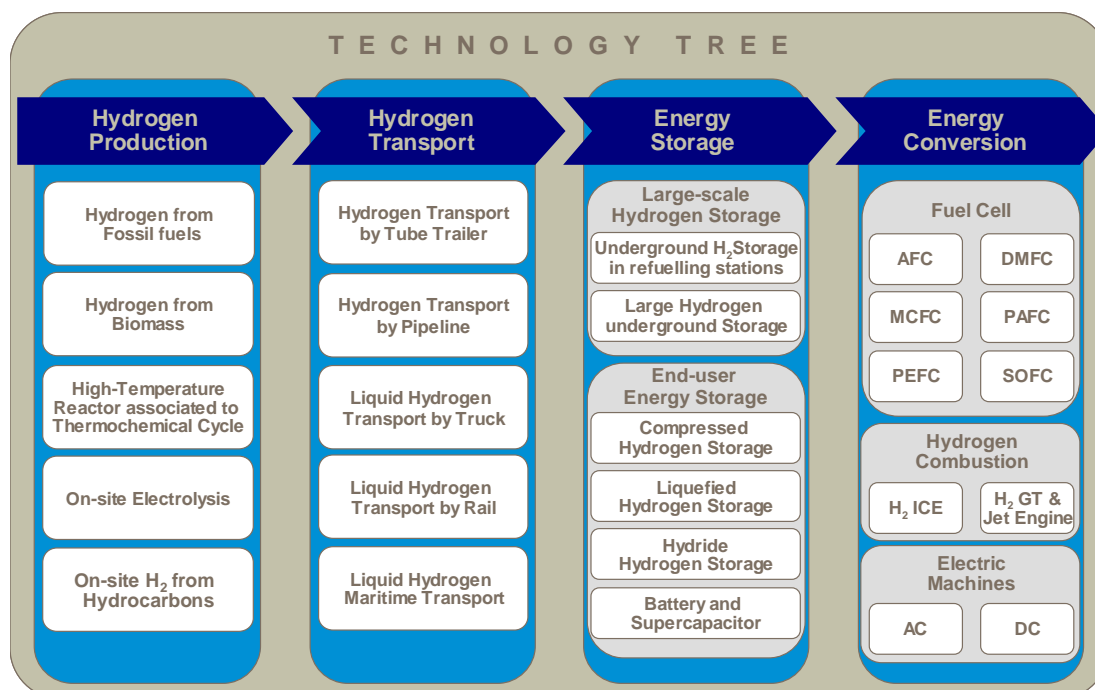


Figure 4.7: Technology Tree structure of the SOTA Wiki [4.9]

The State of the Art assessment is an extensive piece of work, far too broad to be fully summarised here; in any case, it is difficult to generalise on the “adequacy” of the state of the art, because what is adequate in one set of circumstances may be inadequate in another. The SOTA resource (www.ika.rwth-aachen.de/r2h) will remain online for some years (and may be adopted by another future project or action) as a source of information for technology developers.

However, it is worth discussing the SOTA in some key areas perceived by sceptics as being potential “show stoppers”: The cost and durability of Fuel Cells (for any application), and the topic of Hydrogen storage for transport. The availability and cost of more sustainable Hydrogen as a fuel is covered in chapters 5 and 7.

4.4.1 The Cost of Fuel Cell systems

Fuel Cells compete with some very mature technologies such as the Internal Combustion Engine, which are cheap by virtue of a history of almost 100 years of mass production, and the use of cheap materials such as iron, aluminium and plastics. Current demands for clean exhaust emissions and higher fuel efficiency have increased the cost of these incumbent technologies, by effectively mandating the addition of extra components such as exhaust after-treatment, hybridisation technologies (road vehicles) and bottoming cycles (power generation).

The SOTA analysis [4.9] has embraced some of these key benchmark technologies in terms of attributes such as cost. The cost at which the fuel cell is competitive, is a function of its relative efficiency benefit and the cost of fuel. This topic is explored



further in chapter 7, but as a rough guide the “Snapshot 2020” targets from the HFP Implementation Plan [4.10] are:

- Stationary CHP Application c 1MW: €1000-1500/kW
- Stationary CHP application c 1kW: €2000/kW
- Transport application (Car, Bus): <€100/kW

The SOTA study found that recent R&D efforts have resulted in significant reductions in fuel cell system costs. In the stationary sector, two key players are claiming that next generation products for launch in 2009-11 will have costs of around €2000/kW [4.11] using molten carbonate and phosphoric-acid cell technologies; while data for PEM FC costs (Figure 4-8) shows data from both Ballard [4.9] and Johnson Matthey [4.12] indicating the ability to produce a stack (not complete system) for around €50/kw (in this case, these figures are indications of what production costs would be, in high volumes; costs for prototype or low volume systems remain over €500/kW). This picture is encouraging; however, sustained research into both lower cost designs and manufacturing technology is required to ensure that these costs are actually realised both stationary and transport applications

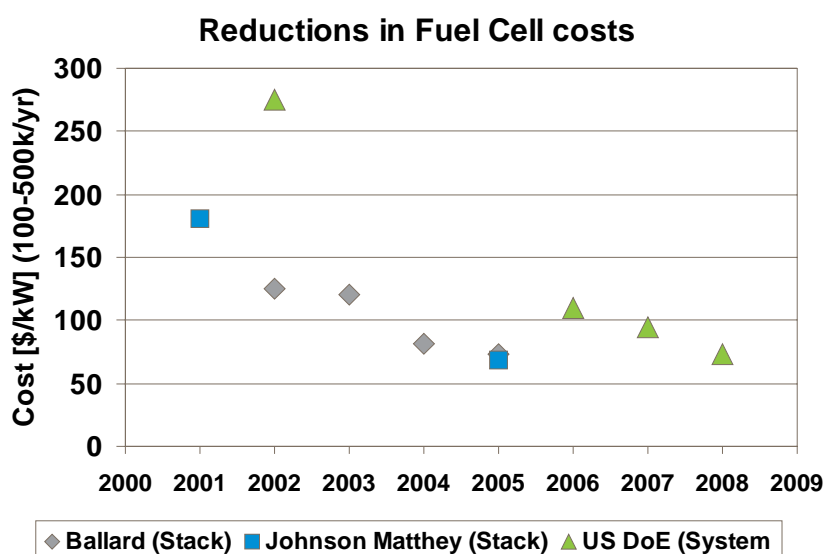


Figure 4.8: Reduction in PEM FC costs [4.9, 4.12] – Stack, 100-500k p.a.

4.4.2 Durability of Fuel Cell systems

Durability needs to match that of benchmark products, under identical real world operating conditions. A passenger car with life of 200,000km requires a fuel cell life of 5000 hours; for a continuously operating CHP system with a life of 10 years, a fuel cell life of 90,000 hours is needed.



Here, SOTA data can be supplemented with “real world” experiences from demonstration projects [4.4, 4.5]. In the “MW scale” stationary sector, such feedback indicates that stack life has improved from a previously typical 25,000 hours to around 60,000 hours [4.5], with availability of over 90% [4.5], and up to 95-98% [4.11] being reported. Makers are claiming that a life of over 100,000 hours will be achieved by next generation products to be launched in 2009-11 [4.11]. Statistics from smaller, kw-scale domestic units are much more disappointing, with poor availability levels as low as 60%, and life of less than 5000 hours, being reported [4.5].

In the transport sector, field trials of the Mercedes A-class F-Cell car [4.4] indicated a fuel cell stack life of 1000-2000 hours in a range of climatic and usage conditions, with typically a failure every 4000km toward the end of the trials. This vehicle has now been superseded by the B-Class F-Cell, which has a claimed stack life of 5000 hours [4.13]. In the bus sector, stack life of over 4000 hours and availability of 99.6% were recorded [4.4]; again, a new generation of bus will supersede those used in the CUTE trial.

So, promising progress is evident in fuel cell durability, and also in the associated field of extremes of high and low temperature operation [4.9]. Further research must translate this progress into durable products made in higher volumes.

4.4.3 Fuel Cell efficiency

Efficiency is one of the key attributes that makes the fuel cell attractive. Some early trials yielded disappointing efficiency results: In the stationary sector, domestic scale CHP systems recorded electrical efficiencies (electrical energy out divided by fuel energy in) of only 26% [4.5], while the efficiency recorded by field trial cars was equivalent to 3.6l/100km of Diesel (on a like-for-like energy basis) [4.4]. To put these results in context, the ideal electrical efficiency of a domestic CHP system is over 40%, while a Diesel-Hybrid car of similar size to the fleet trial vehicles can achieve under 3.5l/100km.

However, such data can be misleading, as they relate to early prototype products which may be non-optimal or engineered with an emphasis on surviving the fleet trial. Other evidence suggests that fuel cell systems are achieving much higher efficiencies. For example, the larger “hot module” CHP fuel cell installed in Hamburg has achieved 46% electrical efficiency [4.14] over its life (which is competitive with the best of other technologies on this scale, with much lower noise and pollution); the new B-Class F-Cell uses fuel with the energy equivalence of 2.9l/100km Diesel, which gives it a “well to wheel” CO₂ performance competitive with the best Diesel-Hybrid technology even if its hydrogen fuel is made from fossil sources (and of course much better with “green” hydrogen).

4.4.4 Hydrogen Storage for Transport

Hydrogen storage technology can essentially be subdivided into three categories:

- Compressed gas storage
- Cryogenic liquid hydrogen storage



- Storage in a solid medium that adsorbs Hydrogen into its molecular structure

Solid storage is a topic that is still very much in the domain of basic research, although first generation systems with limited capability are used in conjunction with pressure tanks in some military applications. It does not appear that solid-storage technology will be ready for a first generation of commercialised vehicles.

Liquid storage is favoured by a minority in transport, and recent developments have included light weight, shaped tanks that fit the vehicle body structure [4.9]. However, the issue of fuel boil-off remains unsolved, meaning that such a fuel tank can lose half of its fuel load in a matter of weeks. This technology could be attractive where hydrogen is shipped in liquid form (see chapter 5), but it should be noted that liquefaction itself is inefficient, requiring one third of the energy carried by the fuel.

Compressed hydrogen storage is the most popular choice for the application of Fuel Cells to transport applications [4.7, 4.9]. Compressed hydrogen tanks are being developed by more than 100 producers of the technology worldwide; most manufacturers producing tanks for gaseous storage provide tanks for hydrogen storage. However, significant challenges still exist for its use in transport applications, where weight and volume considerations are more of a challenge than for stationary applications. On-going developments are centred around the increase of energy density through the use of advanced materials and cost reduction.

In the vehicle itself (excluding compression losses in the refuelling station), the efficiency of high pressure storage is more than 99.9%; only minor energy losses of <0.1% may be expected due to eventual venting and purging of the fuel lines [4.9].

There are many organisations providing storage tanks for hydrogen service at medium pressures (up to 3 MPa), but as the storage pressure increases, the number of industrial players decreases. The first storage tanks at 70 MPa made of composite materials have entered the market. The High Pressure Gas Safety Institute of Japan has recently certified Toyota Motor Corporation's new 35 MPa and 70 MPa high-pressure hydrogen tanks for fuel cell vehicles. Nissan has also certified a 70 MPa high-pressure hydrogen storage system for the purpose of extending the driving range of fuel cell vehicles. 70MPa is the benchmark for the extended vehicle range necessary to create attractive products, but the level of technology required has significant cost and weight impacts.

Unlike for the fuel cell, there is little available information on reducing the cost of hydrogen storage, in terms of current achievements or future projections. The 70 MPa tank is a complex component, involving an impermeable liner, a carbonfibre shell that is robot-wound in a process that takes days, and typically 200 embedded sensors to monitor for the onset of failures. A tank giving 300km range in a car is a bulky component whose shape cannot be adapted to fit available package spaces. Until significant developments occur, it is possible that the tank, more than the fuel cell itself, may define what types of transport application can be successful.



4.5 Emerging Products

To complement the SOTA analysis, a “Technology Watch” review has been developed to follow public domain information on products which are moving towards commercialisation, and the technologies that they contain [4.15]. The Technology Watch covers all the “technology tree” applications, including Transport, Auxiliary Power Units, Goods Handling vehicles, large and small Stationary applications. This study collected information on which companies are advanced in the technology, a timeline for development, and information on when products may be available, along with a discussion on the barriers and drivers for the application. Fully integrated products provide a more robust view of what the technology is capable of in a commercial form. In many cases there may be laboratory developments with greater apparent capability, but that capability can only be considered robustly proven once it is contained in an integrated product.

This study has revealed an extraordinary number of products at prototype or limited production stage, considering that the Fuel Cell sector as a whole is commercially immature. In total, there are more than 40 manufacturers active (meaning having prototypes or low volume products) across the vehicle sectors; the major aircraft manufacturers are engaged in programmes, and a variety of applications have been demonstrated in marine power. In stationary and auxiliary power there are more than 20 active manufacturers, with a number of energy utilities starting to make significant investments in bringing products into use.

And yet, outside the educational toy sector, the study has found just one organisation trading profitably with a Fuel Cell product. This is an important issue – to be considered truly “commercialised”, a product has to be made and sold on a basis that is profitable all the way up the value chain, from parts supply through integration to retail. The definitive challenge for the Fuel Cell in the coming decade is to start showing a different picture with more products being traded profitably.

The results of this study indicate how and where this might happen:

- **The passenger car** is a very important application for Fuel Cells and Hydrogen, due to its ubiquity, which creates both a need and a route to economies of scale. Encouraging progress is evident in terms of technical performance of Fuel Cells (and also Hydrogen ICEs) in the latest field-trial vehicles, and also in terms of the level of commitment displayed by a number of manufacturers. Battery-electric technologies are both a key competitor here and a complementary technology, as seen in recent prototypes with dual fuel (Hydrogen / Electricity) capability. The precise nature of the products that finally become fully and profitably commercialised will depend on the outcome of one of the defining technological battles of the twenty-first century - the battle between the storage of Electricity and the storage of Hydrogen. In the meantime, we will see the advent of niche or image vehicles that may not be profitable but are still commercially relevant.
- **The captive fleets sector (buses, taxis, delivery vehicles)** is known to be a promising early market for Fuel Cells and Hydrogen, because of lower infrastructure dependency and the beneficial effect of local political will on purchase decisions. Perhaps importantly, these early fleets might provide



seeds for the growth of a more extensive Hydrogen infrastructure, linking city centres to highway refuelling. Technical hurdles are similar to the passenger car, although the larger daily operating range of captive fleet vehicles places Hydrogen at a clear advantage over Electricity as a fuel in many cases. The success of the next generation of Fuel Cell and Hydrogen captive-fleet demonstration vehicle will be critical to the success of Hydrogen in Transport.

- **Material handling vehicles** have been identified as a promising near-term market opportunity for Fuel Cells and Hydrogen, especially in addressing the limitations of the incumbent battery-electric technology used in indoor goods handling. On the surface, fuel cell systems for material handling vehicles appear to be on the tipping point of commercialisation, with forward orders for hundreds of units. Several system integrators have produced fuel cell hybrid power packs for electric forklifts and pallet trucks designed to replace the existing battery packs. Technical specifications on these products are publically available through the system integrator websites, although price information needs to be requested. Numerous small-scale fleet trials are now taking place in North America and Europe, and early users appear to like the technology.
- **Two Wheeled Vehicles** could become an interesting early market, especially if transport policy supports the development of markets for zero-emission two wheelers. The usual issues of cost, size, durability and refuelling need to be addressed but this is a less aggressive environment for many of these issues. Battery-electric two wheelers will present a challenge, though as with their four-wheeled counterparts the Hydrogen tank remains a more capable energy store. The sector appears to offer the potential of an untapped global market for basic, low cost but clean individual mobility. Further investment in better products, and the retailing of fuel, is needed in order to exploit this market; but there is a real risk that products developed and made cheaply in China could dominate world markets.
- **Auxiliary Power** for transport applications is an existing, genuine market for the Fuel Cell product, with thousands having been sold to genuine users in the leisure sector without special incentives and on a basis that is probably profitable along the supply chain – and this in itself is still unusual in the fuel cell business. However, there is only one very active supplier selling products right now, and it is a product that requires its own dedicated fuel, and its power output is not sufficient for it to migrate directly from the leisure sector to commercial transport application. To consolidate its success as an early market sector for the Fuel Cell, technological progress in sulphur-tolerant reformers, system cost, size and durability, needs to continue so that APU systems with powers in the 1-10kW range can be realised – perhaps sharing stack components with smaller transport or CHP systems for economies of scale.
- **The marine sector** offers a variety of potential early market applications, ranging from auxiliary power in the leisure and light commercial sector (essentially marinising technologies from the APU sector), to specialised motive power for environmentally sensitive situations. Although these applications are mostly one-off or low volume production, these technologies



might serve a useful purpose in increasing public awareness and acceptance of fuel cell technology. Use of fuel cells in larger commercial shipping applications is still to be proved; this very demanding market (in terms of in-service ruggedness) will not be an early market.

- **The civilian aircraft sector** will not be an early adopter of fuel cell technology. However, given the interest in the technology displayed by two of the world's major aircraft manufacturers, it is likely that fuel cells will appear in aircraft in the future. The most likely applications are hybrid fuel cell APU systems for commercial aircraft, with products appearing around 2020. In the meantime, specialised **military applications** for surveillance will be a small but very high value market.
- **The domestic CHP sector** is an attractive early market for the fuel cell, and publicly stated information gives a clear indication that this sector is rapidly approaching true commercialisation – first products are scheduled to be marketed from circa 2012, with two suppliers having conditional forward orders for tens of thousands of units. There is a strong, well-developed existing market for conventional boiler replacement and, as fuel prices increase, many consumers will be looking to adopt money-saving technology. A key test will be whether these first products deliver on “business case” and durability; in this sector free-piston Sterling engines are a challenger technology but they have their own issues of cost, durability and vibration. In the long term, this sector could be threatened by super-insulated homes, heat pumps and solar water heating, but given the lifetime of housing stock this does not limit the market for several decades.
- The **Industrial and Commercial market sectors** offer a huge potential for growth for fuel cell technology as the distributed generation expands across the globe. Fuel cell products for industrial and commercial co- and tri-generation applications are already available, and claims for a next generation product appear promising (if unproven in the public domain). However the strong, well-developed market for the conventional product combined with the higher purchase price for the fuel cell systems is limiting the market penetration for fuel cell technology. Further R&D on reducing fuel cell system costs by using modular components and on improving fuel reformer technology will improve the prospects for fuel cell technology in this sector. Suitable Government policies and subsidies may also encourage the shift from conventional to new technology.
- The **Back-Up Power and UPS market sectors** have great potential for growth and early penetration is under way. There are several fuel cell systems already available in the market place, which can compete on an equivalent basis with the incumbent technology, as demonstrated by the much publicised IdaTech / Ballard / ACME forward order. However, for fuel cell systems to establish a firm market share in this sector, the technology must be proven to be reliable, durable and at a price that can be justified on a life-time basis.
- **Portable Fuel Cells** is an interesting early market for Fuel Cell and Hydrogen technology. Education kits are already commercially successful and there are



indications that the technology is breaking into the Toy market. Fuel cell technology offers significant advantages compared to current battery technology in terms of reduced weight and higher energy density. This is helping to drive the development of the technology especially for military applications. Several military fuel cell products have already been tested in the field. Technology developed for the military is likely to spin out to the commercial sector over time, and a couple of portable fuel cell battery chargers have been launched over the past year.

Table 4.2 shows a summary of Technology Watch information on forward orders and commercialisation level.

Table 4.2: Technology Watch commercialisation summary [4.15]

| Sector | Attribute-ready prototypes ⁽¹⁾ | Product on Sale | Product Fully Profitable | Forward Orders ⁽²⁾ | Mass Production |
|-----------------------|---|-----------------|--------------------------|-------------------------------|-------------------|
| Leisure APU | Now | Now (one range) | 2008 | Retail sale | Limited potential |
| UPS | Now >10 OEMs | Low volume now | Estimate 2010-15 | 10,000 (IdaTech) | 2010 on stated |
| Micro CHP | Now >10 OEMs | 2011 stated | Estimate 2010-15 | 87,500 (Ceres, CFC) | 2011-12 stated |
| Industrial CHP | Now >10 OEMs | Low volume now | Estimate 2010-15 | Believed 100's | 2010 on stated |
| Fork Lift | Now – 5 OEMs | Low volume now | Estimate 2012-17 | Believed 100's | Estimate 2015-20 |
| Scooter / Bike | Now >10 OEMs | Low volume now | Estimate 2010-15 | Retail sale | Estimate 2015-20 |
| Bus | Now – 7 OEMs | Low volume now | Estimate 2020-25 | No – HyRaMP poss. | Estimate 2015-25 |
| Car | Now - 9 OEMs | 2014-5 stated | Estimate 2025-30 | Not yet... | Estimate 2025-35 |
| Small Portable | Now >40 OEMs | Some retail now | Estimate 2009 | Mostly Retail sale | 2008 on stated |

⁽¹⁾ In most cases some effort is still required to fully validate durability; numbers refer to major players

⁽²⁾ Forward orders are conditional on prototype performance targets



5. Energy Resources and Infrastructures

5.1 Why Energy Resources and Infrastructures matter – and how the project studied them

The use of hydrogen as a fuel is part of a much larger picture involving the development of a sustainable supply of energy to all sectors of the economy that consume it. The reason for this is that hydrogen is produced from other energy resources, and so it is effectively in competition with other users of those resources. It is therefore impossible to consider the supply of hydrogen without considering the bigger picture of energy supply.

Why is Hydrogen an “Energy Vector”?

Hydrogen is a form of fuel that can be used in burners, boilers, internal combustion engines (piston engines or gas turbines) and Fuel Cells. It burns or reacts with air to produce water, often (but not always) with very low levels of other emissions.

Hydrogen is, however, not an energy resource – it has to be produced from other sources of energy. One of its attractions is that it can be made from so many different primary energy sources (in fact, it can be made from every primary energy source).

Primary energy sources are the resources from which energy is “harvested”. They include:

- Fossil fuels – Coal, Crude Oil, Natural Gas
- Nuclear power (using the energy stored in fissile Uranium)
- Renewables – Wind, Solar, Tidal, Wave, Geo-thermal and Bio-mass

Energy Vectors (often described as fuels) are made from these primary sources as a way of transporting them to consumers in a more usable form. The most common are:

- Refined Gasoline, Diesel and LPG fuels
- Refined Bio-Diesel and Bio-Ethanol based fuels
- Electricity, distributed via utility grids
- Natural Gas (the only primary source that is distributed directly by utilities)
- Firewood (surprisingly common in the developing world) and pelletised bio-mass
- In the future, hydrogen as a compressed gas or cooled to a liquid form



Therefore, Roads2HyCom undertook a series of studies to develop further understanding of Energy Resources from which hydrogen can be made, and the Infrastructures available to distribute it. Information from these studies was fed into later parts of the project. The studies were structured as follows:

- **Mapping of existing hydrogen technology demonstration project sites**, as these are likely to be the seeds for further development, to start developing an understanding of their relation to existing infrastructures and resources
- **Study of existing industrial hydrogen production and distribution scene**, including an analysis of potential industrial hydrogen surpluses and mapping of existing industrial distribution infrastructure. This is important as the existing hydrogen supply industry continues to be a major source of fuel for early hydrogen-fuelled markets
- **Study of the development of low carbon energy resources**, including wind energy, biomass, fossil fuels with carbon-capture, and nuclear energy; to establish their future potential to supply energy for hydrogen production in addition to their existing consumers. This is an important topic in the light of growing general demand and pressure to reduce the carbon footprint of other energy vectors like electricity which may compete for low carbon resources
- **Study of some key interface issues** in energy supply, including the transport of hydrogen, the development of electricity grids (especially in the context of growing distributed power generation), and the mitigation of short and long term energy peaks/troughs (for which hydrogen is an option).
- **Creation of cost models** for hydrogen production by various means

5.2 Mapping of Hydrogen Project Sites

Demonstration projects can be seen as showcases for both the Fuel Cell and Hydrogen technologies and the policies that support them (as explored in the next chapter), and help to bridge the gap to commercial sustainability.

In this study, data on hydrogen demonstration projects were collected from various sources and synchronised with the, currently, largest database for demonstration projects, which is held by the technology platform HFPEurope [3.5]. More than 140 data sets were collected, and tagged with a geographical reference using the NUTS code [5.1].

The geographic mapping revealed some “obvious” clustering, with centres of aggregation in the German Rhein-Ruhr/Rhein-Main area and Denmark in connection with southern Sweden (see Figure 5.1). This clustering is interesting in the context of the location of production and distribution infrastructure, but many successful projects located further from this fixed infrastructure demonstrate that co-location is not essential.

This work fed into further analysis of the project site characteristics [5.2, 5.3], which are also studied in greater depth in the next chapter.

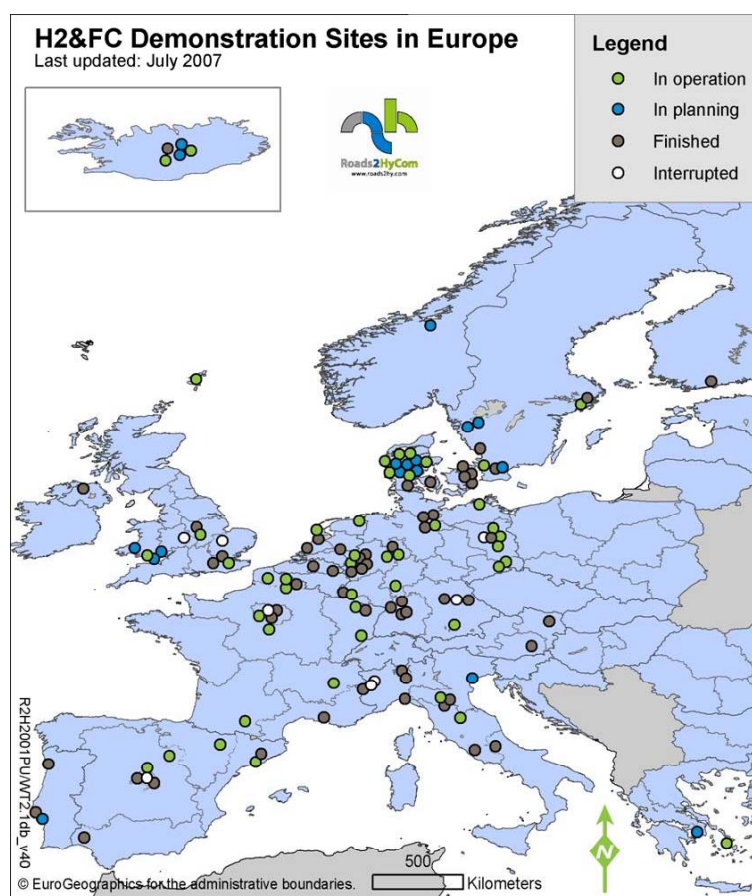


Figure 5.1: Map of Hydrogen technology demonstration sites [5.1]

5.3 Current Hydrogen Production, Supply and Distribution

Hydrogen is often thought of as a hard-to-obtain, futuristic fuel, but in truth it is a well-known commodity in the chemical process industry, being used in (amongst other things) the refining of oil, production of fertiliser, and the manufacture of metals. As an interesting (though irrelevant) statistic, the total European production of circa 80-90 billion cubic metres per year is equivalent to the fuel consumption of around a third of the European road vehicle fleet.

This hydrogen is of course consumed by the processes for which it is made, and is in any case often of unsuitable quality for use in a fuel cell. However, if small over-capacities exist in some of the supply chains in this sector, its large overall size means that it is a potential source of smaller quantities of hydrogen that is readily available. The main three players in the hydrogen market are merchant companies (which trade hydrogen), captive producers (which produce hydrogen for their direct customer or their own use), and by-product hydrogen producers (which provide hydrogen resulting from other chemical processes).

The Roads2HyCom study [5.2, 5.4] indicates that significant quantities of hydrogen could be available to support early and transitional phases of Hydrogen Economy



development. This so-called "surplus" is the result of cumulative small capacity excesses in existing plants, and by-product hydrogen currently put to use for heating (a role that could be fulfilled by a variety of other means, while remaining overall positive on carbon saving), and could amount to 2-10 billion nm^3 per year. Such a conclusion needs to be treated with caution, because the estimation methods used are imprecise, the demand for hydrogen for oil refining is rising (due to the need to remove sulphur from transport fuel – there is anecdotal evidence of a hydrogen supply shortage in some regions), and finally because much of this surplus or overcapacity does not relate to hydrogen in a purity suitable for fuel cell use. However, if only 5% of the lower range of surplus were available (5% of 2bn m^3 , or 100m m^3), this quantity could fuel over 25,000 cars or 1,000 buses. This would be sufficient for very significant "Hydrogen Community" or extended demonstration activity, but some of the more optimistic scenarios for hydrogen uptake indicate that these numbers of vehicles are desired well before 2020 [3.3, 7.1].

The geographic distribution of all identified hydrogen production sites was mapped as part of the study, using the same NUTS code basis as for the "technology demo" projects described previously. At the current scale, the geographic location of hydrogen consuming projects is not so much an issue – liquid hydrogen transport is used to ship fuel across Europe – but if usage rises toward the order of 25,000 vehicles as indicated above, clustering these larger consumers nearer to existing infrastructure could be more important.

In association with this work, the project mapped and created on-line databases of all the production sites, pipelines and fuelling stations [5.5], with key data on their capacities. These databases can be accessed at www.roads2hy.com.

Nearly 1,600 km of hydrogen pipelines in Europe could be identified [5.5]; mainly in the form of 15 larger pipeline networks owned by Air Liquide, Linde (BOC), Air Products (Sapio) and some smaller network operators. They are located in the areas of high production density shown in Figure 5.2. The total volume of industrial merchant hydrogen supplied by trailers or cylinders in Europe is estimated at 425m m^3 [5.5], or less than 1% of total production; while the total hydrogen liquefaction capacity is still relatively low at less than 100m m^3 per year.

These statistics yield some interesting observations: First, the fuel consumed by 25,000 vehicles may be sufficient to favour pipeline distribution over short distances (up to circa 100km, [5.8]), especially if existing pipelines form the basis of that distribution network. If the vehicles are used farther from production infrastructure, liquid transport is preferred, but the fuel used (100m m^3 per year) is equivalent to all the existing liquefaction capacity in Europe. Therefore, unless demand builds close to pipelines or liquefaction capacity can be increased, the increase in use of industrial hydrogen as a fuel could be constrained by these factors.

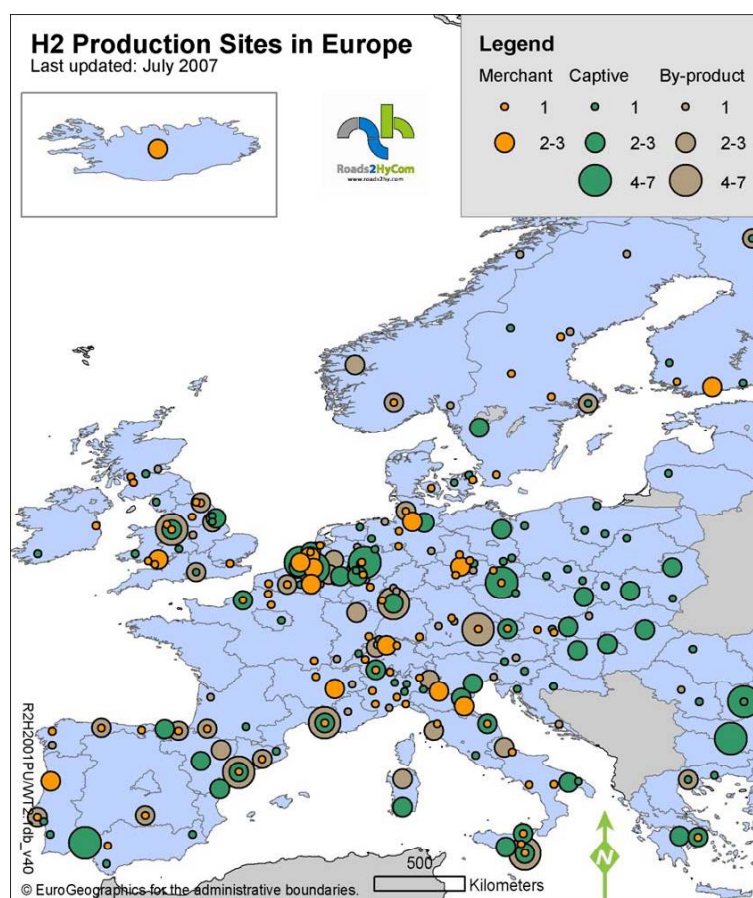


Figure 5.2: Geographic distribution of industrial Hydrogen production [5.4]

5.4 Potential for de-carbonised and sustainable Hydrogen supply

As discussed in Chapter 4 above, reducing the carbon footprint of the hydrogen supply is an important factor in making it attractive as a fuel. Within the project, a study was made of the potential for renewable and potentially CO₂-neutral energy sources to contribute to the environmentally neutral production of hydrogen in Europe up to 2020/2030 [5.6]. This time frame is relevant, because it represents the transition between larger demonstration projects (considering in particular Transport, where hydrogen is most significant as a fuel), and early stages of higher-volume commercialisation of hydrogen-using applications.

The study therefore looked at the development status and available technologies in solar, wind, ocean, hydro, biomass, and geothermal renewable energy, nuclear hydrogen production processes, and hydrocarbon based hydrogen production with carbon capture and sequestration (CCS), all of which may have potential to contribute to carbon-free and carbon-lean hydrogen production at the time scale investigated. The availability of carbon-free energy sources for hydrogen production will general depend on three key factors:



- **Their technical and commercial maturity** now, and the development potential that can be mobilised up to the target time span
- **The time needed to install new production capacity** (including planning and time needed to acquire building and operating permits)
- **The competition from various other energy demand markets** (in particular, grid electricity and synthesis of low carbon liquid fuels) for carbon-free energy

Because of this third point, it was assumed as a working hypothesis that these sources will always face this demand in direct competition to hydrogen supply. Considering this competition in a “steady demand” framework, it is almost universally concluded that greater carbon abatement is achieved by using the resources for electricity generation; it is also important to consider that for air and sea transport prime-movers, the challenges of hydrogen technologies are so high that a sustainable liquid fuel (derived from biomass) may be preferred. Therefore the main objective of the analysis is the search for potentials of carbon-free/low-carbon energy that may be available in excess of the demands of the electricity grid or liquid synthetic fuel production, due to geographic (stranded resource) or temporal (peak/trough) factors. This potential would lend itself to ‘green’ hydrogen production without constituting a competition to the important task of lowering the carbon emission from, in particular, electricity production and liquid fuels.

5.4.1 Electricity producing energy sources

Most currently used renewable energy sources fall into this category, in that they deliver hydrogen using electricity as an intermediate step, to power an electrolysis process. Solar, wind and wave energy all have a fluctuating nature, which poses challenges to their grid integration. It can be found from analysis of the capacity factors and simulation calculations [5.6], that above a fraction of 25% and 15% of contribution to demand, wind and PV power, respectively, will regularly cause abundance of energy production that is not immediately matched by electricity demand. This potential might then be branched out of the electricity market and used for hydrogen production without interfering with carbon displacement in the electricity grids. Wave energy and some hydro sources would be expected to fall into this category also. These are some of the most promising sources under the competitive scenario described above; the synergy of hydrogen production and grid balancing is explored further in Section 5.5.3.

Geothermal and reservoir-buffered Hydro power are well established as sources of electricity generation, but as they offer better control of production, they are better suited to the task of de-carbonising the base-load (and peaks, for fast response Hydro storage) of the electricity grid, so have limited potential for hydrogen production until the time of a carbon-free grid, which is expected to be well beyond 2030. An exception would be islands or remote regions where the export of electricity is not possible.



5.4.2 Gas producing processes

These are processes that use either renewable hydrocarbons (biomass-derived) or fossil fuels with carbon capture, to produce hydrogen via a reforming or separation process.

Carbon Capture and Storage (CCS) technologies are being proven today in first small power station units. Fossil fuels (normally coal) are converted to a synthesis gas, which may then be reformed to produce hydrogen and CO₂ for capture. In a CCS power plant, the hydrogen is used primarily to drive a gas turbine for low carbon power generation, with the waste heat from the turbine being used to drive the gasification and reforming processes; in principle, the power station can be re-optimised so that there is enough of this waste heat to produce a surplus of hydrogen that can be exported from the plant as a fuel (as a guide, a 400 MW power station is said to be capable of producing enough surplus to fuel 1,000 buses or 25,000 cars, although this fuel production would be traded off against extra electrical generation capacity and so has to be more economically attractive). This is a promising approach in that there is a clear synergy between de-carbonising the electricity grid and supplying hydrogen, and it is the topic of the Dynamis project [3.4]. However, the challenges of reduced efficiency of coal use, and high cost, remain unsolved. According to industry time-lines [5.6], this technology is not expected to be competitive in the market before 2030, which indicates that it has limited potential as a hydrogen production route in the time frame considered.

Biomass, when considered in the context of total energy demand, is a rather limited source of energy with low energy density of the raw materials. Taking the current discussion on the competition of energy crop and food production into account, and inevitable demand for biomass to synthesise liquid fuels for sectors like air transport, shipping and freight haulage where hydrogen is far more challenging to implement as a fuel, it is expected that Biomass will have limited potential for hydrogen production in the timeframe considered.

5.4.3 Processes that produce Hydrogen directly

High temperature production of hydrogen, be it by solar or nuclear processes, has been investigated in some depth. Nevertheless, no processes have been proven at technically relevant scale. New nuclear power stations in Europe are today being regarded as replacements for outdated and technically unsafe reactors, and would be favoured to supply the base load of the electricity grid due to the steady, slow-response nature of their output. No additional plant is today visible that could cover additional demand for electricity for electrolysis of hydrogen. The Generation IV reactors necessary for high temperature processes are still under development. Considering the considerable lead times for nuclear plant planning and commissioning, hydrogen production from nuclear energy is unlikely to be favoured until after 2030.

5.4.4 Discussion of Potential

On the basis of the assumptions described above, the total potential of carbon-free energy for hydrogen production is concluded to be in the order of 50 to 100 TWh p.a. up to 2030 [5.6]. This equates to around 8-12% of the “mature market” demand for



2050 (Chapter 7), so it is broadly consistent with where a de-carbonised supply needs to be in 2030, if it can be realised in practise. This supply will consist mostly of offshore wind energy with the possibility of a considerable contribution from wave energy if this source is developed. In both cases, there appears to be a strong potential for synergy of hydrogen production with grid load management, both in terms of time-based load (peak-logging) and geographic issues (grid overloads). Post-2030 a further considerable increase of renewable energy can be expected, maybe supplemented by electricity from coal-powered plants with CCS, if this technology can prove its maturity.

These findings presume a “level playing field” in terms of the value attached to carbon emissions, which is not the case today. It remains possible that high taxation of conventional transport fuels, above the levels of the energy sector, could drive strong development of other hydrogen supply routes (such as steam reforming and electrolysis), at least as an interim measure, if the prevailing economics favours it. Likewise, policies that prioritised Energy Security over Climate Change might favour the diversion of further low-carbon energy toward hydrogen production, even though this would be less efficient in carbon-footprint terms. Whether this happens depends on policies implemented in the meantime.

5.5 Hydrogen in a future interconnected energy infrastructure

5.5.1 Transporting Hydrogen

Current sources of hydrogen, whether they are merchant sources from the chemical industry, or pilot projects designed more specifically to produce hydrogen as an energy vector, are generally not linked as a cohesive infrastructure to supply hydrogen as a fuel. As demand for hydrogen as a fuel grows, better integration of the hydrogen production chain may be required to ensure a cost-effective, robust and environmentally efficient supply is maintained.

To capture the broader picture of the technology, this part of the study analysed the interactions of distributed European hydrogen production sources with the existing power generation infrastructures, in particular looking at three critical issues: The transport of hydrogen, the development of the electricity grid, and energy storage at grid level.

The reviews of hydrogen transportation [5.5, 5.7, 5.8] revealed that accepted wisdom on transport mode appears to remain valid: Compressed gas tube-trailer trucks are the preferred form of distribution for low demands and close distances (below 200 km), whereas liquid trucks are more suitable for intermediate demands and medium to long distances; pipelines become economic for higher demands at whatever distance. The investment required for a pipeline construction is an economic barrier that is only partially reduced with the introduction of polyethylene (PE) pipes in the distribution networks.

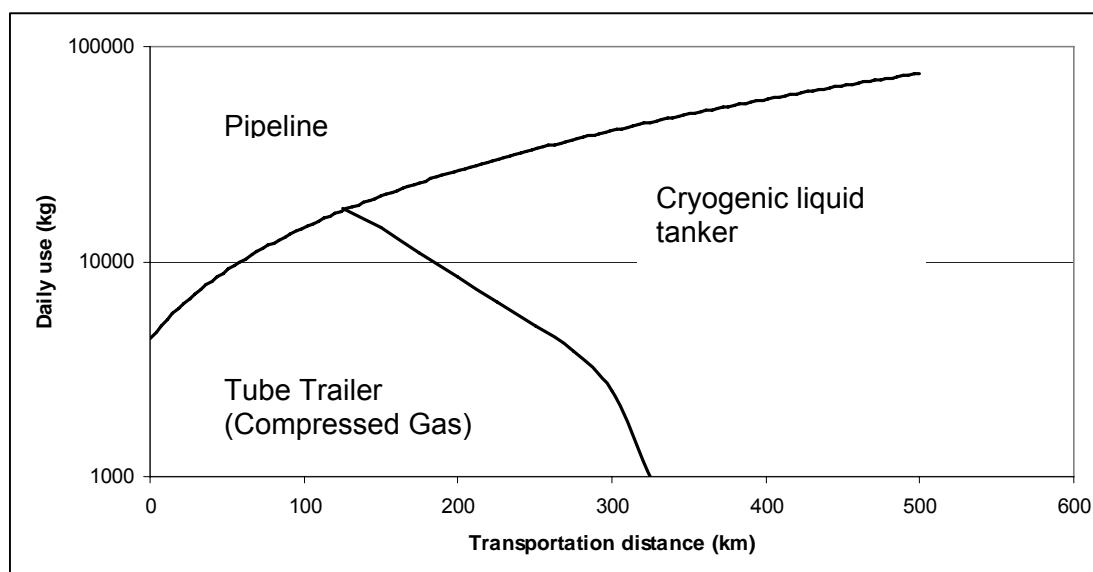


Figure 5.3: Guidelines for Hydrogen transportation from Ogden et al [5.8]

There are, of course, important caveats in using such guidelines. Firstly, not all sources of hydrogen have a liquefaction plant, and total liquefaction capacity today (most of which is of course in use already) is sufficient for fulltime fuelling of only circa 25,000 cars or 1,000 buses, as described above. Secondly, such guidelines are very much influenced by local circumstances (for example, existence of a partial pipeline infrastructure or heavy tolls for transportation trucks), and the prices of steel and haulage fuel. The key messages here are twofold: the relevant hydrogen supply stakeholders (production, liquefaction, distribution) need to be closely involved in plans for infrastructure build-up; and research needs to continue to bring down the cost of extending the pipeline network.

Research can also play a role in bringing forward further transportation technologies: the use of solid storage for transportation (as well as for the end-user fuel tank); and the use of hydrogen mixed at low percentages into the natural gas supply, either for use in standard gas appliances (including fuel cells in future), or for re-separation at point of use. This topic has been the focus of the NaturalHy project [5.11], whose results have indicated that this approach could be attractive despite current poor performance of the separation technology.

5.5.2 Hydrogen and Distributing Electricity

The electricity grid is likely to play a major role in a future hydrogen supply infrastructure [5.7, 5.9], for a number of reasons:

- Many of the low-carbon or sustainable energy resources needed for future production of hydrogen are, in fact, sources of primary energy for electricity generation



- Localised production of hydrogen by electrolysis is being considered using grid electricity as a power source
- And linked to these above issues, it is possible to combine the function of hydrogen production with use of hydrogen to store energy at times of peak supply (especially from intermittent renewables like wind energy) and then re-convert it to grid electricity at times of high demand (using a fuel cell)

Existing electricity grids have been built for a model of centralised power supply and distributed consumers. However, a new and growing production segment is that of decentralised or distributed generation [5.9], including sources fed with fossil fuels (predominantly natural gas), and sources making use of renewable resources (RES). In the case of grid connected devices, intelligent control systems are needed to balance supply and demand and prevent accidental “islanding” of a part of the grid disconnected for maintenance. Solving these challenges is an essential component in the successful uptake of fuel cell based co-generation technologies on the domestic to industrial scale (1kW-1MW). These technologies are seen as a potentially important early market for the fuel cell, as a dedicated fuel infrastructure is not required, and asset utilisation is high. Therefore policies and standards need to be in place to allow such distributed control to be effective.

On the other hand wind and solar farms, so called aggregated structures, are generally distant from consumers and dependent on transmission networks [5.9]. Still often remotely located, they feature a special intermediate case between centralised and dispersed generation. As wind, solar (and wave and tidal) energy are resources that one would wish to harvest when they are available, the grid connection issue here is not just one of control, but of distributing the energy (requiring an effective policy on reinforcing grid capacity and connectivity) or storing it locally until it is needed (or can be sold at a more attractive price).

5.5.3 Hydrogen for Energy Storage on the grid

Electricity is a difficult energy vector to store directly on a large scale. Batteries and super-capacitors have high costs, low energy densities, and require expensive power-electronic systems to create alternating current electricity for the grid. Hydrogen has been proposed as a possible storage medium, by combining production for “export” (e.g. to a transport application) with the ability to re-convert hydrogen back to electricity when required. The rising use of renewable energy, which is often intermittent in nature, increases the potential need for such systems.

This part of the study [5.7, 5.10] looked at such a hydrogen-based system versus competitors such as compressed air, pumped-hydro, batteries and other technologies. The study considered two types of storage need:

- **Surplus power storage**, which is necessary to handle the mismatch between load and power production, thus avoiding an overloading of the grid due to lack of transmission capacity. Timescale is “hours to days”. It is predicted that gross surplus power from renewables only arises above a penetration level of 25% (wind) or 15% (photovoltaics) [5.10]. This penetration is rarely exceeded at large-scale; policy for renewables [2.1] indicates that storage of this nature will not be required until well after 2020



- **Interim storage**, which is needed to reduce short fluctuations or to allow the shift of power supply to peak load hours. Timescale is minutes to hours. Analysis of fluctuations shows that small-scale storage can balance the major part of the short-term fluctuations very well [5.10]

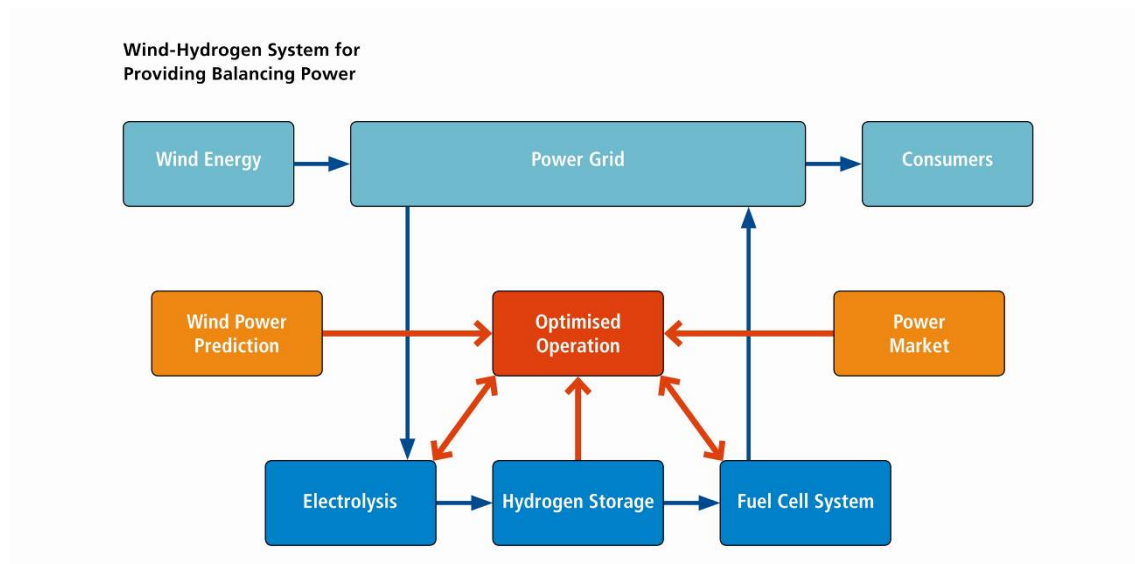


Figure 5.4: Schematic for hydrogen based energy storage at a wind farm [5.10]

The study demonstrates that no single storage technology can satisfy every requirement, and that a mix of fast response and long term storage is likely to develop. The demand for surplus power storage cannot be determined at this moment due to a lack of data for the future development and technical details of new production capacities in power generation and the electricity grid.

As a storage mechanism, hydrogen offers “round trip” efficiencies of no more than 50% (Electricity returned per electricity put in), compared to up to 80-90% for some other systems. However, in contrast to other storage options, Hydrogen offers the advantage of a high flexibility and the possibility for multiple-use, for instance being delivered as vehicle fuel. In some circumstances this could therefore prove to be a favoured solution especially if there were a demand for the (intermittent) waste heat that arises from the inefficiency.

The issue of surplus energy on a longer timescale will start to occur at a European scale when the share of renewable electricity is further increased well above the 35% envisaged for 2020. Then, though, hydrogen can play an important role due to the possibilities of long-term, low-loss storage and, again, the ability to integrate this function with what could, by that time, be a substantial transport fuel supply need.



Table 5.1: Competitors to Hydrogen as an energy store for the grid [5.10]

| | Compressed Air (CAES) | Pumped-Hydro | Flywheel | Lead Acid |
|---|---------------------------------------|---------------------------------------|-------------------------------------|-----------------------------------|
| Physical / Chemical principle | Mechanical - potential energy storage | Mechanical - potential energy storage | Mechanical - kinetic energy storage | (Electro-)chemical energy storage |
| System voltage | Low, medium | Medium, high | Low, medium | Variable |
| Range of capacities [W] | High MW to GW | High MW to GW | Low kW to high kW | Low kW to medium MW |
| Discharge time | Hours | Hours | Minutes | Minutes to Hours |
| Energy density [kWh/m³] | n/a | n/a | 10 –20 | 20 – 80 |
| Lifetime [cycles] | ~ 10000 | ~ 50000 | ~50000 | < 1000 |
| Energy efficiency [%] | ~55 for non adiabatic storage | ~80 | ~90 | ~75 (incl. self discharge) |
| Capital cost per unit power [\$/kW] | <1000 | ~1000 | ~300 | <900 |
| Capital cost per unit of storage capacity [\$/kWh] | <100 | ~100 | ~5000 | <1000 |

5.6 Structures and Trends for the Cost of Hydrogen

A hurdle often cited for the widespread uptake of hydrogen as a fuel is its high cost. Complex production, distribution and refuelling processes, and embryonic demand volumes (compared to liquid fuels) could mean high operating costs for hydrogen users despite the inherent efficiency of the fuel cell if this is the chosen energy converter.

Other studies such as the HyWays roadmap [3.3] have indicated that economies of scale can reduce costs. However, events of 2008 (meaning the unprecedented peak in energy and raw material prices, followed by an equally unprecedented fall) have highlighted the importance of being able to understand and model cost structures on a dynamic basis.

The project therefore undertook an exercise to break down cost structures for hydrogen, and construct models capturing all the elements of cost. First, current cost structures were reviewed, based on literature and public domain commercial data [5.12]. Then models of cost were constructed for a selection of promising production routes, embracing steam reforming of natural gas, electrolysis from various electricity sources, and direct production from biomass and nuclear energy [5.13].

The intention of this study was not primarily to present yet further estimates of current or future hydrogen costs (although this has been done in Chapter 7 as a means of studying the “total cost of ownership” proposition for fuel cell products), but to



elaborate the calculation procedures themselves. Sample results are largely illustrative, but have been cross-checked with other studies such as data from the US DoE [5.13].

Table 5.2: Example cost model: Costs for the provision of energy: wind farm offshore [5.13]

| | Abbreviation | Formula | Numerical value | Unit |
|--|--------------|-----------------------------------|-----------------|-------|
| Economic boundary conditions | | | | |
| Electricity costs | s | | 0,091 | €/kWh |
| Interest rate | i | | 8,00 | % |
| Depreciation period | T | | 15 | years |
| Annuity factor | a | $i * (1 + i)^T / ((1 + i)^T - 1)$ | 0,117 | - |
| Basic data | | | | |
| Full load hours | v | | 3.000,00 | h/a |
| Power output | P | | 1.000,00 | kW |
| Annual Energy Production | AEP | $P * v$ | 3.000.000,00 | kWh |
| Capital expenditure | I | | 1.890.000,00 | € |
| Annual costs | | | | |
| Annuity | AN | $I * a$ | 220.807,84 | €/a |
| Power costs | S | $s * 1\% * P * 8760 \text{ h}$ | 7.971,60 | €/a |
| Costs for service and maintenance | W | $I * 2,5\%$ | 37.800,00 | €/a |
| Miscellaneous costs (insur., equipment...) | SK | $I * 1\%$ | 18.900,00 | €/a |
| Total operating costs | K | $S + W + SK$ | 64.671,60 | €/a |
| Total annual costs | AK | $AN + K$ | 285.479,44 | €/a |
| Specific costs for Wind offshore | | | | |
| Costs of Wind energy production | $k_{[kWh]}$ | AK / AEP | 0,095 | €/kWh |

Because cost structures present such a complex picture, it is impossible to draw simple conclusions. However, the following trends are evident:

- Production routes based on fossil fuels (with sequestration) remain potentially the cheapest – reinforcing the urgency of commercialising CCS processes sooner than current projections
- Fuel price figures most strongly in fossil-based routes, whereas capital costs are more prominent for renewables – meaning that unstable energy and raw material prices will make for difficult decision-making regarding the viability of one route over another
- Distribution costs form a significant part of the picture, more so than for liquid fuels – hence the economics of retailing may be more strongly dependent on location

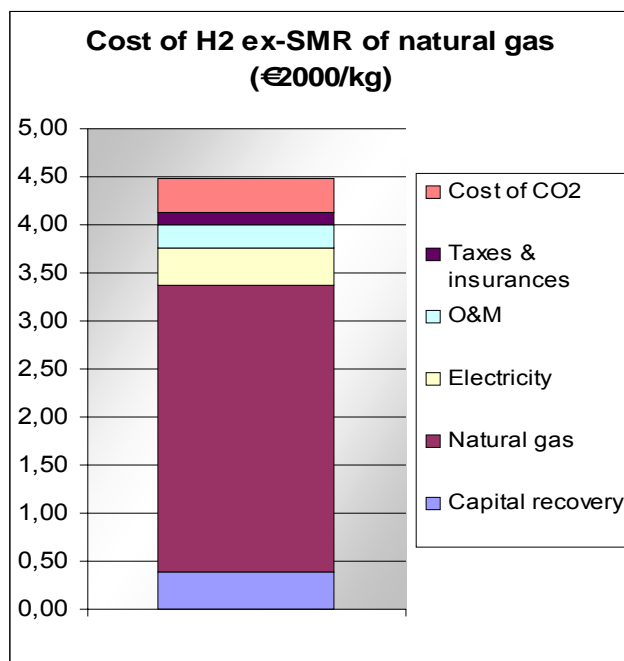


Figure 5.5: Cost breakdown for 2030 SMR [5.13]

The implications of hydrogen cost for the attractiveness of fuel cell applications is discussed in Chapter 7.



6. Early Adopters of Fuel Cells and Hydrogen

6.1 Why Early Adopters matter – and how the project studied them

Early adopters are important in the gestation of any new technology, as they can provide feedback to improve the product, a critical mass of uptake to reduce its cost, and publicity for the virtues of the technology. In the case of Fuel Cells and Hydrogen (and particularly the latter), early adopters tend to be community-based projects, which are government-sponsored or supported by major corporations (or both), often linking together application and fuel supply. There are exceptions to this rule, principally in natural gas fuelled combined heat-power and in warehouse vehicles, where the potential “business case” has been strong enough to drive a current or imminent genuine market for the technology.

What is a “Hydrogen Community”?

A “Hydrogen Community” is a group of bodies or legal entities, who are stakeholders in or potential operators of, or carriers for, hydrogen infrastructure, supporting hydrogen applications of varying nature (this also includes infrastructure and applications relating to hydrogen-rich fuels), and who together create a constitute cluster of hydrogen and fuel cell activities that support each other. In practice such Communities could be Regions, Cities, Remote locations (such as islands), Self-contained entities (airports, seaports, industrial complexes, etc.), or Distributed entities (hydrogen highways, etc). In a Hydrogen Community, hydrogen plays a significant role in the community as an energy vector. A Hydrogen Community may evolve out of, or in parallel to, large Demonstration or Lighthouse Project(s). Possible cluster activities within the Community can include fundamental or applied research and demonstration projects, which feed new technology into the Community. Community projects tend to embrace:

- A clear focus on deployment and/or directly meeting end-user energy needs through integrated hydrogen-related energy conversion systems and pathways
- Strong stakeholder participation as demonstrated through an ongoing cooperation between local authorities, local agencies, economic operators and other local stakeholders
- Potential long term sustainability of the project/initiative

Projects which include the use of Fuel Cells but not Hydrogen have not been excluded, but these are less infrastructure dependent so the Community aspect is not always as relevant.



A concept of Sustainable Energy Communities (SECs) [6.1] has been developed within the context of the European Commission initiative CONCERTO [6.2]. The objective of CONCERTO is to “support local communities, as clearly defined geographical areas or zones, in developing and demonstrating concrete strategies and actions that are both sustainable and highly energy efficient”. The main impulse for this European initiative is “the strong desire in all communities, among politicians, planners, energy service providers, and citizens to develop and demonstrate high degrees of decentralised energy supply, integrated with renewable energy sources as well as the conscientious application of leading energy efficiency measures in various end-use sectors”[6.2].

SECs are “local communities in which politicians, planners, project developers, market actors, and citizens actively cooperate to develop high degrees of intelligent energy supply, favouring renewable energy sources, with a conscientious application of energy efficient measures” [6.1]. SECs can be instrumental to the realisation of a sustainable energy system, since its participative approach can ease the transition from a current unsustainable energy system towards a future sustainable energy system. Moreover, SECs act as a showcase for the integration of innovative energy technologies. As potential SECs, all communities represent an important setting for the development and deployment of sustainable yet disruptive technologies.

These community-based early adoption projects are an important step in the route to broader commercialisation. They tend to be naturally disposed towards long-term thinking, with consideration of wider social and environmental implications of the new technologies; they are well placed to undertake infrastructure build-up; vehicles tend to operate in captive fleets that are easier to refuel; and the strong involvement of local government is an enabler both for public acceptance and the promotion of infrastructure and knowledge clusters in the area. Therefore Roads2HyCom undertook a series of studies to develop understanding of the driving forces, needs, capabilities and other characteristics of these communities:

- **A database of community-based early adoption projects** was compiled via an inventory exercise using existing public sources and databases on hydrogen and fuel cell projects, as well as an on-line survey (“Communities Registration”), which was publicised via European organisations such as the Technology Platform HFP Europe [3.5] and the European Hydrogen Association (EHA). The database captures basic information about current and potential future projects [6.3, 6.4]
- **Detailed interviews** of selected projects were then used to capture further information, including feedback on the organisational and logistic experiences of these projects [6.5]. (It should be noted that feedback on the operational performance of technologies themselves was treated as a separate topic, as described in Chapter 4).
- **Profiling:** Finally, analysis was used to profile different types of communities, and generate conclusions regarding likely needs and success factors for each, in the form of a “Scoping Catalogue” or self-assessment framework for potential projects [6.6]

In addition to these activities, the project ran a number of workshop events in association with the European Commission, the HFP, HyLights and HyRaMP



(Section 3.3), involving people connected to community-type initiatives. These workshops were used to disseminate findings of the above studies and receive feedback.

6.2 Landscape of Community Projects

From the inventory exercise a database of 96 hydrogen and fuel cell projects was generated, of which 36 were deemed suitable for further analysis [6.4] as early adopter communities, on the basis of broad selection criteria (see “What is a Hydrogen Community?” above) and status of project development [6.3, 6.4]. The robustness of this data, in particular completeness of geographical coverage, was crosschecked against project partners’ knowledge.

The geographic distribution of projects (Figure 6.1) tended to be “as expected”, with the largest number in Germany, followed by Italy, the UK and Spain. In terms of the 36 projects deemed to have the most potential as early adopter communities, Germany also dominates, together with Italy and the group of Nordic countries. Notably, Germany is characterised by few, but larger early adopter communities, where several initiatives are grouped under a single coordinated community (often regional) activity. On the other hand, Italy and the Nordic countries tend to have a greater number, but small-sized communities (Figure 6.2).

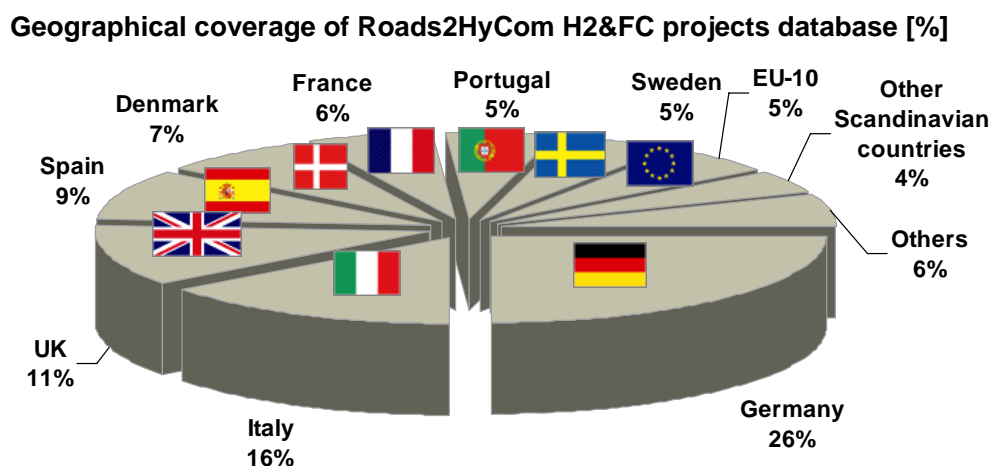


Figure 6.1: Geographical coverage of database [6.3, 6.6]

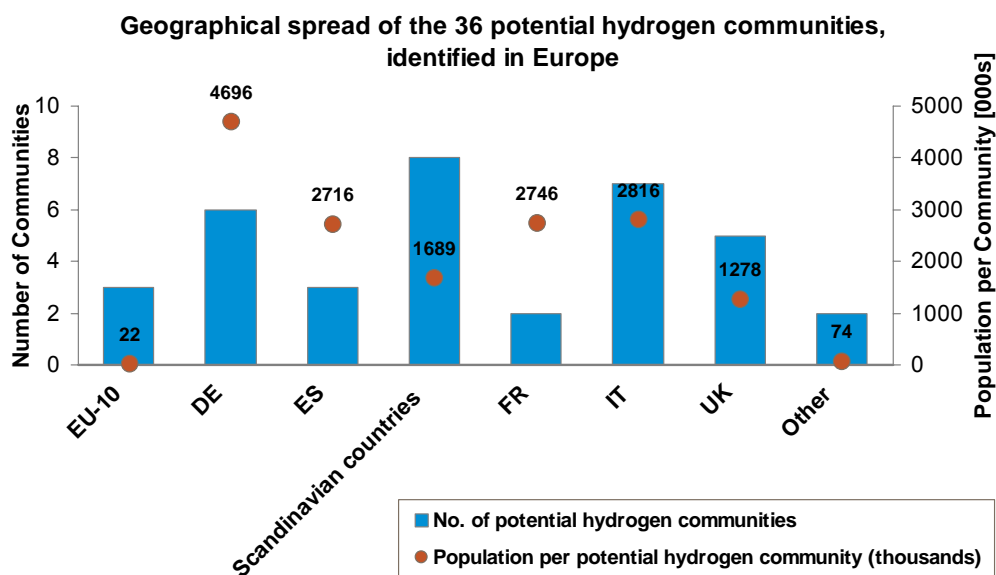


Figure 6.2: Hydrogen Communities and Population data [6.6]

The project also mapped known installed (stationary) fuel cells by number and capacity (reference year 2006), and found that Germany had almost 75% by number and two-thirds by capacity in the EU-27 (Figure 6.3).

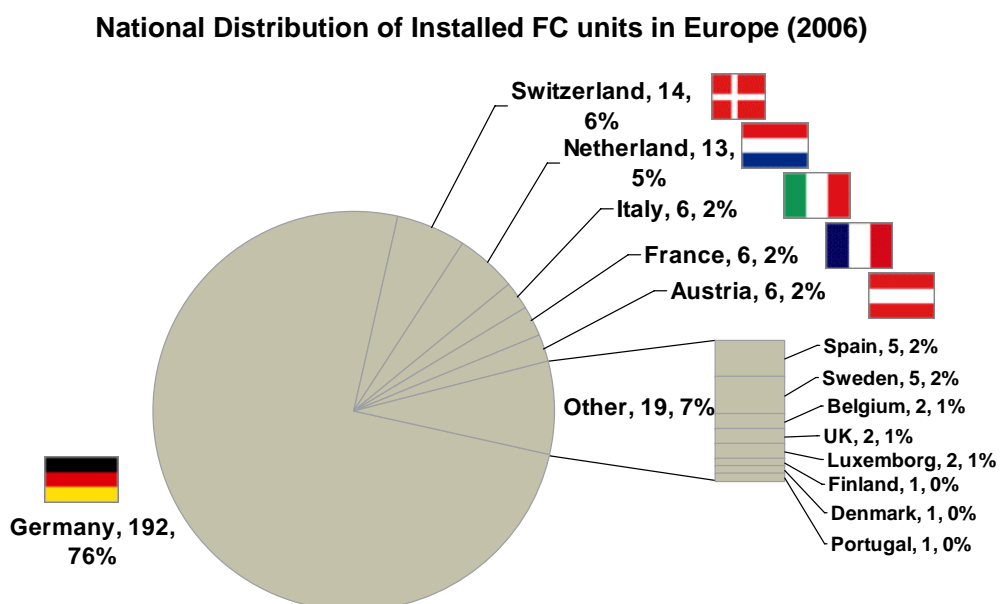


Figure 6.3: Geographical distribution of installed fuel cells in Europe [CoreTec]



In terms of the sample of (36) early adopter communities, other features of note are:

- 25% of the communities were existing projects (some with proposed up-scaling), 50% were in the initiation phase, 25% were proposals; indicating a potential for a ramp-up in this type of initiative
- Government is the numerically largest stakeholder (Figure 6.4), indicating that such projects tend to be strongly dependent on both local political will and related fiscal support
- 58% of the projects featured multiple applications (i.e. *both* transport and stationary type projects); next most popular were transport-focussed (31%, mostly public transport), followed by Stationary (11%, mostly heat-power)
- 47% of the projects had a Regional focus, 36% were Cities, 17% were Islands

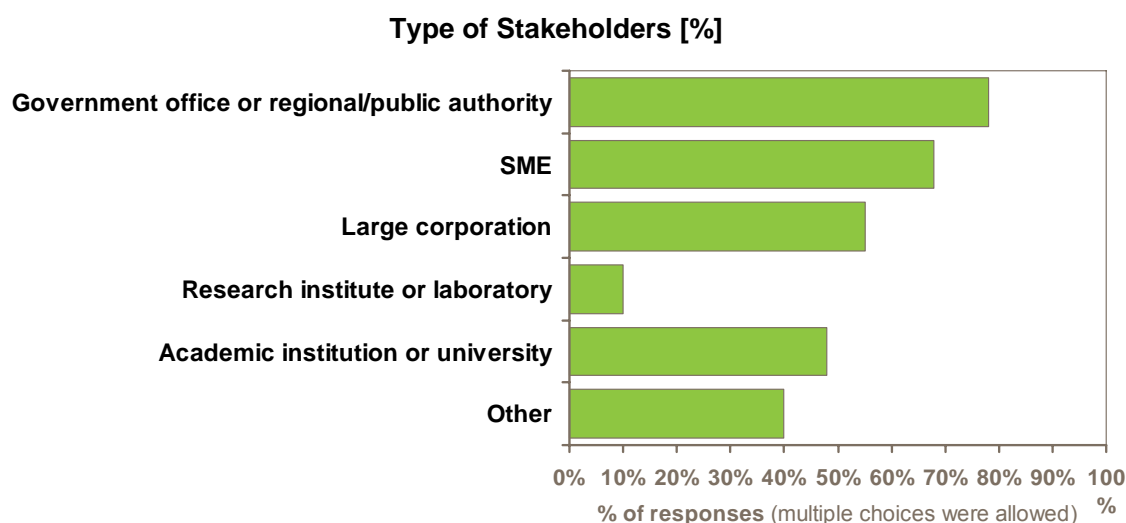


Figure 6.4: Stakeholders in the community projects (refers to originally selected 40 communities from which final 36 were chosen) [6.3, 6.6]

Finally, this part of the study looked in some detail at funding and financing issues arising out of the results from on-line survey ("Communities Registration"). Issues of funding, both from the public and private sector, were strongly cited in the on-line survey as the main barrier to success for the projects, featuring 2-4 times more frequently in responses than other issues such as access to technology hardware or expertise. The majority had annual project budgets of less than € 1 million p.a., with just one project above € 5 million. Government grants featured most strongly in responses on sources of funding (Figure 6.5), with national and regional funding being the most popular grant-funding responses; however, funding from the private sector (meaning the support of industrial partners) also featured in 85% of all responses.

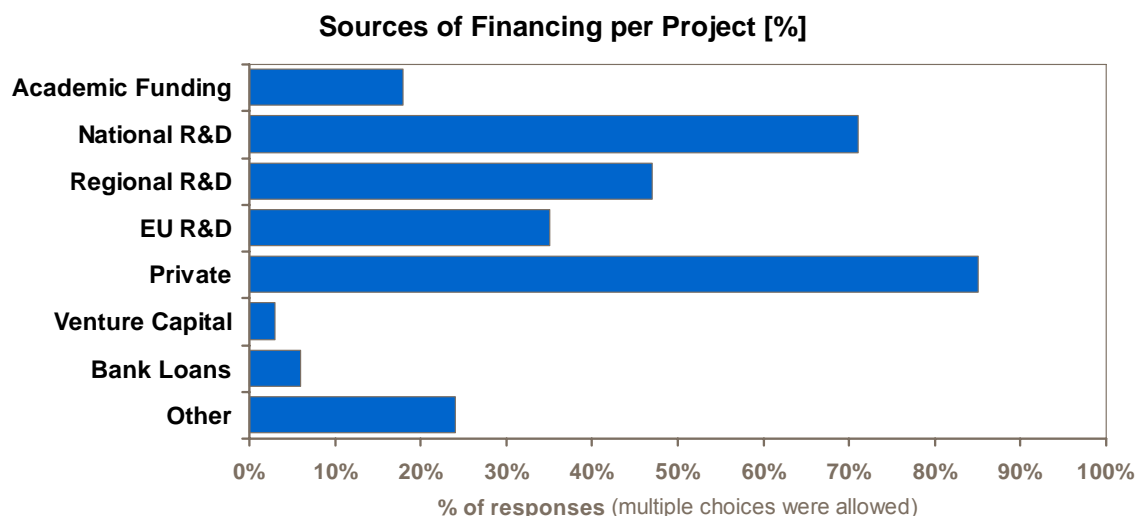


Figure 6.5: Analysis of community project funding / financing [6.3, 6.6]

6.3 Experiences from Community Projects

Fourteen projects from the database were selected for further structured questioning on their experiences [6.5]. This questioning was based around the generic Roads2HyCom metrics (Section 3.2), with specific questions being devised under the umbrella of each metric category.

The most important message from this exercise is that there is an enormous wealth of learning that other potential communities (including those in other future energy sectors) can benefit from. Roads2HyCom has attempted to capture that learning in the Handbook for Communities described in Chapter 10. Key findings were:

- **The presence of local Political Will** (at regional and national level) is an absolutely critical factor, in cases such as hydrogen where the technology is still in a relatively early stage of adoption. Although political will can be driven by the direct existence of a specific locally un-met technical need (such as air quality improvement) or capability (such as local industry), other factors (such as the enthusiasm of an empowered individual or group) could be just as important. Political will can equate not only to access to government funding, but to easing passage through hurdles such as obtaining permission for installations.
- **Public acceptance** within the local community is also a very important factor, with many important lessons having been learned “the hard way” in this field. Of course, poor public acceptance among voters is likely to lead to erosion of political will.



Table 6.1: Lessons learned from community projects [6.5]

| METRICS | LESSONS LEARNED | |
|---------------------------------------|---|--|
| | IN GENERAL | SPECIFIC TO HYDROGEN COMMUNITY PROFILES |
| Technology Accessibility | <ul style="list-style-type: none"> Local ownership and access to required technological knowledge is of great importance Require long-term contingency plans for accommodating plant, maintenance, upgrading errors and so on | <ul style="list-style-type: none"> It seems more difficult to ensure the accessibility to technology and knowledge from component suppliers if the project is in a remote areas, such as islands |
| Public Acceptance | <ul style="list-style-type: none"> Early involvement of the community helps to solve a number of problems that might arise, ensures local political support and facilitates the overall process of project implementation Concrete realisation of the demonstration plant fosters increased public acceptance, goodwill and reduces the 'fear-factor' | <ul style="list-style-type: none"> Islands and regions seem to be more focused on creating a community commitment to the project than larger cities. An explanation for this may be that projects in cities are, to a larger extent, carried out by larger companies whereas on islands project promoters often have a stronger local anchoring |
| Political Will | <ul style="list-style-type: none"> Political support from local, regional, national and/or supranational institutions is very important when setting-up and carrying out the demonstration project, from the point of view of: <ul style="list-style-type: none"> ✓ Mobilising awareness to environmental / renewable energy (EU/National) ✓ Promoting public acceptance ✓ Assisting projects through non-technical barriers | <ul style="list-style-type: none"> No differences between community profiles have been registered Differences between national and regional financial structures / systems under which the demonstration project takes place can affect the importance of the support at different levels |
| Potential for Community Growth | <ul style="list-style-type: none"> The interviews only show vague indications of emerging ties between businesses, suppliers and associated institutions. This might be because it is still too early to expect any cluster development from a couple of demonstration projects. | <ul style="list-style-type: none"> Communities with a strong 'driver' for security of energy supply, such as remote islands, are more likely to expand in size A 'driver' to create jobs and to promote local and regional industry appears to be stronger in regions and in islands than in cities In the case of cities, a 'driver' to promote the city as environmentally-friendly seems to be the main project driver |



6.4 Profiling of Hydrogen Communities

A profiling exercise was conducted on the 36 selected communities [6.4], with the aim of characterising them in terms of both their “drivers” (underlying motivation for implementing fuel cells and/or hydrogen) and “capacities” (inherent ability to accommodate these new disruptive technologies, including both technical and economic strengths).

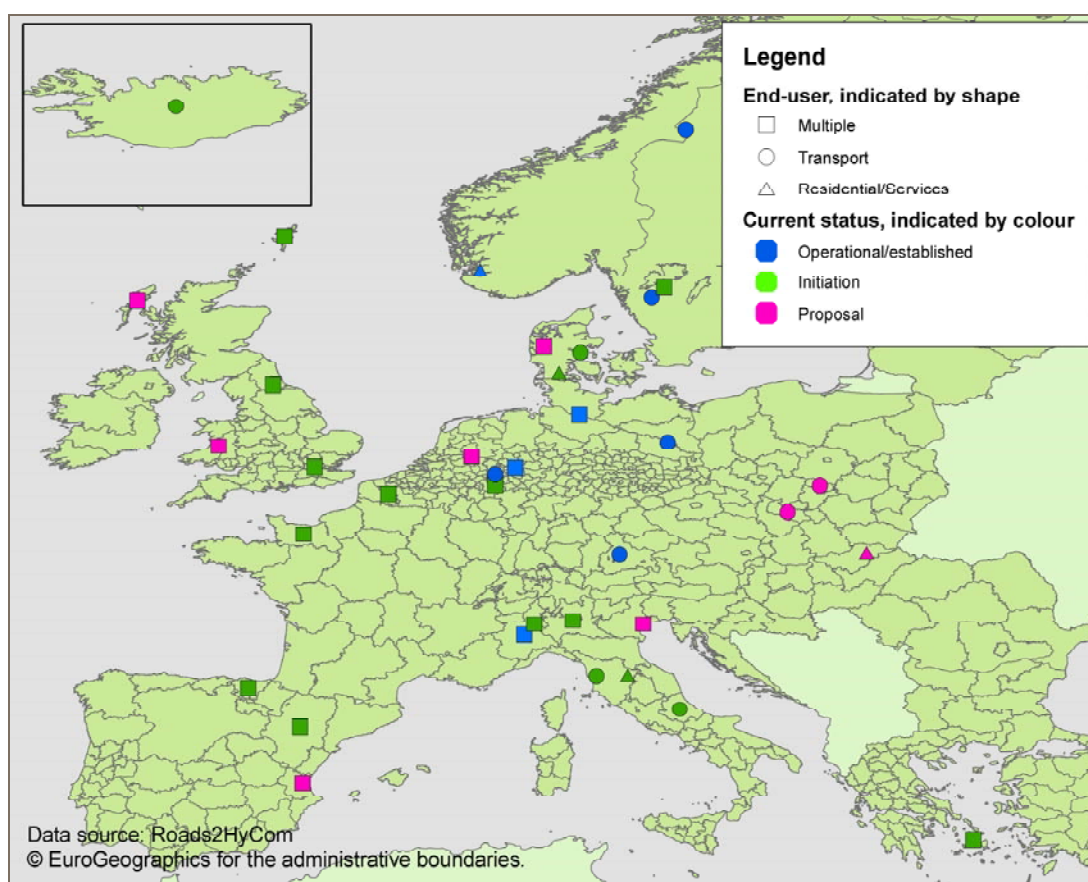


Figure 6.6: Landscape of selected projects [6.6]

Once again the Roads2HyCom framework of “metrics” was employed, with each being assigned detail definitions and classified as either a “driver” or a “capacity” [6.4]. Weighting factors were then used to aggregate scores in “driver” and “capacity” categories, so that each community could be plotted against axes of “driver” and “capacity” (see Table 6.2). The objective here was not to pick “winners” from the list of 36 communities, but to look for generic trends amongst them – for example, whether all possessed both high drivers and high capacities.



Table 6.2: Weightings for Capacity and Driver metrics (illustrative) [6.6]

| Metrics | Capacity | | | Driver | | |
|--|----------|---------|---------|--------|---------|---------|
| | Cities | Regions | Islands | Cities | Regions | Islands |
| Technology Accessibility | | | + | | | |
| Global Environmental Impact | | | | | + | |
| Local Environmental Impact | | | | ++ | + | |
| Capacity & Availability | | | | ++ | + | ++ |
| Cost | | | | | | |
| Public Acceptance | + | + | + | | | |
| Political Will | ++ | ++ | ++ | | | |
| Security & Sustainability | | | | | | ++ |
| Potential for Growth A: Employment | | | | + | + | ++ |
| Potential for Growth B: Cluster Development | ++ | ++ | + | | | |

A readily apparent dividing factor for the 36 communities was one of geography, as they all fell into one of three categories: Cities, Regions and Islands (note: the term “island” is also used to encompass remote communities that are not strictly islands in the geographic sense). As each of these three categories will place different emphasis on its drivers and capacities, the analysis was effectively split by category, with different aggregation weightings for each.

Each type of community has its own characteristic on the driver/capacity spectrum, which is the result of its circumstances as reflected in the metrics and weightings.



Island communities tend to show a balance of capacity and driver, with their strongest capacities being public acceptance and local political will, both of which derive from their insular nature. Security of energy supply, and the desire to create and protect local technology-sector jobs, are the strongest drivers. The frequent presence of stranded local renewable energy (wind in the north, sun in the south) in islands provide synergies for hydrogen sector and thus act as a supplementary driver in these types of communities.

Importantly, islands have relatively low energy intensity and growth, thus their drivers tend best to be served with the implementation of multiple applications, as a single end-use sector/application type does not typically provide large scope for technology adoption (and derived benefits). An important success factor for islands is the ability to retain knowledge and skills locally. Considered in isolation, Islands can make good pilot projects for new energy technologies; however, reproducibility in a form relevant to the majority of Europe's more urban population can be limited. The "showcase effect", particularly in popular tourist locations, is also a relevant factor.

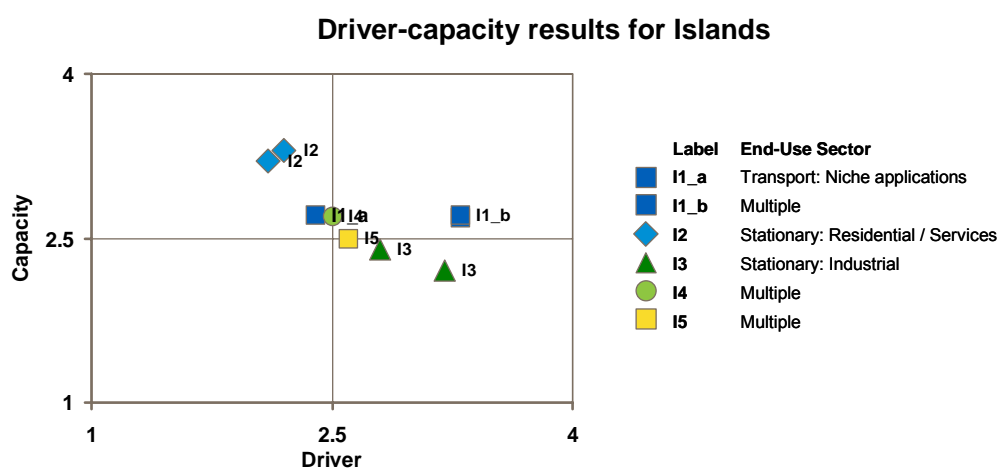


Figure 6.7: Capacity / Driver relationship for Islands [6.6]



Regional based community initiatives tend to show very strong Capacity, with access to technology, political will and public acceptance featuring most strongly (usually as a result the presence of local industry, research institutions or energy resources), along with the ability to interconnect individual initiatives within the region. Unlike Island communities, security of energy supply is not a strong driver for Regions – the strongest drivers tend to be Growth Potential and a desire to tackle Environmental Issues, especially in view of rising demand in the region.

For these reasons, Regions naturally favour initiatives tuned to their local legacy, whether that be a cluster of industries or technologists, or a local energy-related resource. A Region often embraces both urban environments (which can benefit from initiatives in transport and district combined heat-power) and suburban or rural surroundings (which may contain major industries or energy resources). They offer powerful scope for expansion (into neighbouring regions) or reproducibility (in other regions with a similar legacy), and often have access to very significant regional political will, and the government funds to support it.

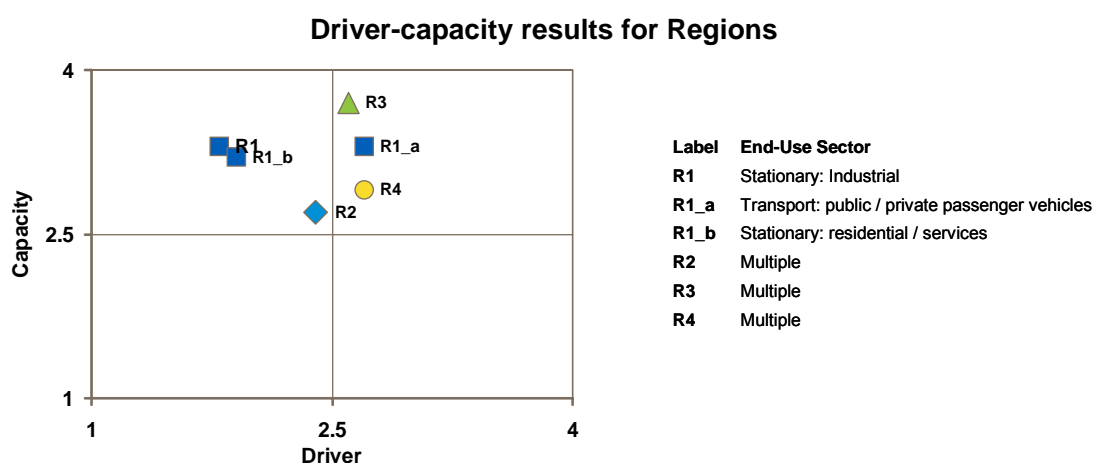


Figure 6.8: Capacity / Driver relationship for Regions [6.6]



Cities tend to show the strongest driver/capacity mix, scoring highly on almost every individual metric. As with Regions, they tended to show great strength (capacity) in access to technology, a positive response from the public and politicians, and the ability to grow an initiative. Again similar to regions, environmental issues (both local, such as air quality, and global, such as greenhouse gases) are strong driving factors, combined with the desire for city growth to be more sustainable. A few individual cities showed less favourable performance, and here the analysis indicated weaker political support as a major problem factor.

Cities therefore tend to favour solutions to urban problems, for example the greening of public transport. The public profile of such initiatives tends to be good, as they operate in an area of dense population, all of whom can potentially benefit. However, cities in isolation tend not to have their own energy resources within the city limits; in the long term, linkage to sustainable energy supply at regional or national level is essential.

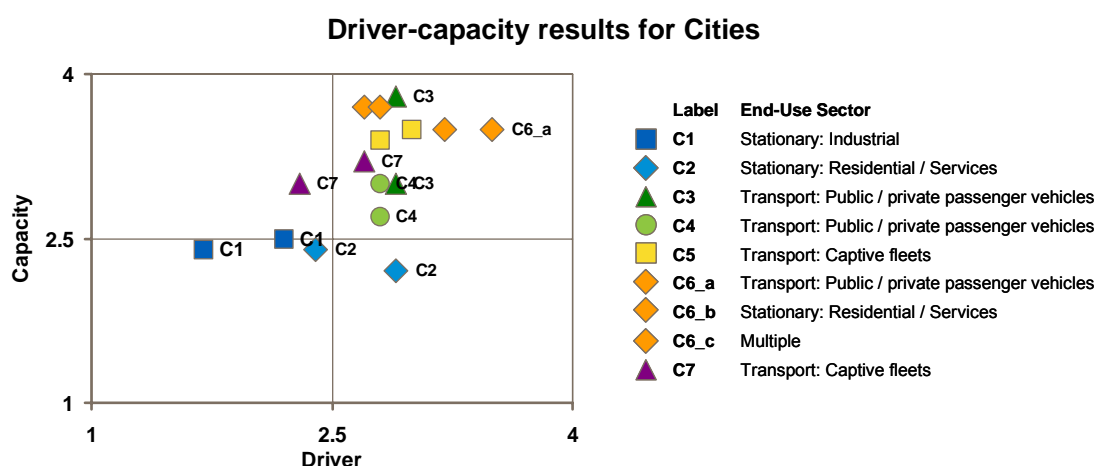


Figure 6.9: Capacity / Driver relationship for Cities [6.6]

All these community types are characterised by strong support from local authorities, high involvement from the citizens, and strong perspectives for local cluster development. Independent of the community type, the first two factors are crucial for successful new technology integration. A strong position for cluster development is also an important facilitating factor, given the presence of a local energy innovation industry, and related knowledge.



7. Technology pathways for Fuel Cells and Hydrogen

7.1 Why technology pathways are important – and how Roads2HyCom studied them

Unless they are creating a brand new market, new and disruptive technologies have to compete with and displace incumbent technologies if they are to be successful. In the case of Fuel Cells and Hydrogen, those incumbent technologies (most often internal combustion engines and fossil fuels, but also electric power and batteries) tend to be very mature, benefitting from low costs derived from high production volumes, and high reliability resulting from accumulated engineering and manufacturing expertise.

It follows that, in any given application, a certain combination of conditions is required for the new technology to become attractive. The objective of this part of Roads2HyCom was to explore what those conditions are. Conclusions drawn can be used as inputs to, for example, recommendations and conclusions for research, for the energy supply, or for the approach taken by government-supported early adoption initiatives – which are the topics of the next three chapters.

Roads2HyCom approached this analysis by a combination of the following:

- **A compilation of scenarios** for the uptake of Fuel Cell and Hydrogen technology, in order to give context to the time-frame in which mass adoption should be studied [7.1]
- **A study of regional factors**, in order to establish how these might influence the development route or tipping-point for the uptake of the new technology [7.2]
- **Construction of key characteristics** (costs, environmental performance) of likely main **future energy chains and typical applications**, in the light of recent developments in energy and raw material prices [7.3, 7.4]
- **Identification of Gaps, Opportunities and Synergies** by analysis of energy chain-application pairings to compare aggregate environmental performance and capital cost / fuel cost relationships, with similar data for future incumbent technologies [7.5]



7.2 Scenarios for the uptake of Fuel Cells and Hydrogen

7.2.1 Time based scenarios

A compilation and comparison of scenario, roadmap and pathways studies, and R&D plans envisaging Hydrogen as a future energy carrier, was constructed to create a backdrop for the analysis that followed [7.1]. The work looked at the timeframe 2010-2050, and in particular drew upon published work from the International Energy Agency (IEA), the European project HyWays [3.3], the US Department of Energy, the Hydrogen and Fuel Cell technology platform (HFP) [3.5, 4.10], and Japan's 'Strategic Technology Roadmap (Energy Sector)'.

All the reviewed studies foresee the main application - 75% or more - of hydrogen is in the transport sector, projecting that by 2050, between 30% and 75% of vehicles will be hydrogen fuelled. Stationary use of fuel cells is foreseen in CHP applications, but these mainly use natural gas or synthesised / bio-sourced substitutes as a fuel.

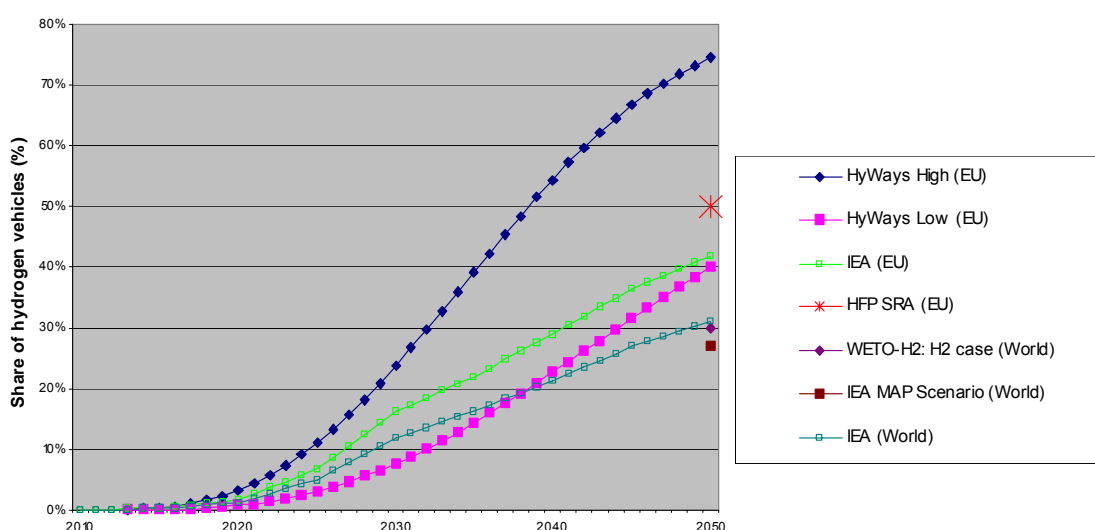


Figure 7.1: Vehicle parc penetration scenarios for hydrogen fuel [7.1]

The analysis indicates a consensus that hydrogen does not enter the energy mix unless there is a stringent climate policy, the oil and gas prices are high, and there is adequate progress in technological learning. Most studies indicate that hydrogen introduction into the energy mix starts with the use of by-product hydrogen, supplemented by decentralised production by reforming of natural gas or by electrolysis of water. Around the 2025-2035 period, a number of critical transitions are foreseen, as low carbon energy sources, centralised production, and structured distribution networks start to arrive in line with the onset of mass-market uptake of hydrogen-fuelled technologies. Importantly, the studies reach quite different conclusions about the pace at which renewables displace fossil fuels – one study



suggests that 80% of hydrogen will come from Natural Gas in 2050 (albeit with carbon capture and sequestration – CCS), another indicates that 90% will come from Renewables and Nuclear, with an approximately equal split. These differences of view reinforce the importance of embracing hydrogen production in long term European energy policy – according to these studies; total European Hydrogen demand in 2050 will be between 2 and 5 Exajoules (EJ, 10^{18} Joules) per year, or 555,000-1,400,000 GWh (gigawatt-hours) per year. This is 3-7% of the EU-27's energy consumption in 2005.

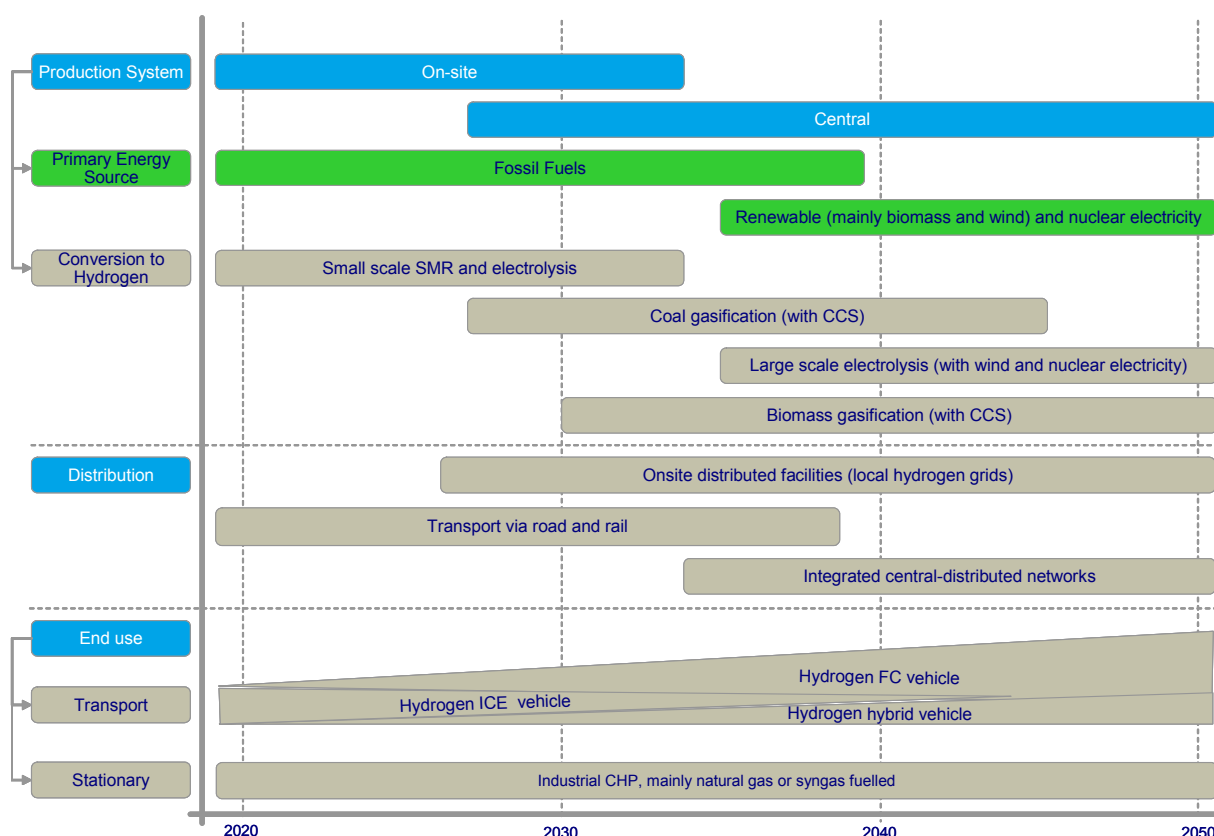


Figure 7.2: Snapshots of Hydrogen uptake in Europe [7.1]

7.2.2 Regional factors

Chapter 5 demonstrates the importance of regions and municipalities as early adopters of Fuel Cell and Hydrogen technology. Often these regions or municipalities have a local legacy of regional factors, which could potentially influence the attractiveness of new technologies and, by implication, the development path taken by products that use those technologies.

Roads2HyCom therefore undertook a further study of regional factors [7.2], looking in particular for links between characteristics of regions and their success in sustaining Fuel Cell and Hydrogen projects. The study looked at both the Transport and



Stationary sectors, and found no strong link between regional capacities and drivers related to technology, and the continuing success of projects; a conclusion that is completely in line with the findings of Chapter 6. The implication for the “technology roadmap” is that these regional factors do not have any particularly significant influence on the course of technology development.

As a result of these findings, the Roads2HyCom project revised its approach to postulating a roadmap for technology evolution. No further account was taken of specific regional influences; instead, further analysis of technology evolution was based upon non location-specific measures such as cost-effectiveness, environmental impact and technology maturity. While it remains likely that regional factors do influence what is needed of technology (for example the relationship between areas of high wind energy or biomass harvesting and a possible future hydrogen production route), the implied needs at technical level can be assumed to be mostly generic. In simple terms this means that a functional specification for a Fuel Cell and Hydrogen application such as a city bus or CHP plant is generic, even though the envelope of that specification is influenced by regional extremes such as climate or usage profile. This in itself is an important conclusion – successful Fuel Cell and Hydrogen products need to be engineered for global application, even if local political will promotes clusters of early adoption.

7.3 The Source to Tank component

Roads2HyCom has studied the potential of a number of hydrogen production routes, including an in-depth review of the potential of low-carbon sources (Chapter 5, [5.6]), and a review of future scenarios for the ramp-up of supply infrastructure (previous section). Most of the likely future pathways are well known, but the economics of production will change as rising fossil energy prices and cost reductions driven by competition and economies of scale exert competing influences. Where fossil fuels are used as the primary energy source, there will be increasing political pressure to reduce the green house gas emissions which are the main drawback of these pathways, and the cost of carbon-capture will start to become a factor in the economics of both hydrogen and other energy vectors.

So this part of the study [7.3] looked in more detail at the likely evolution of hydrogen production pathways (including distribution, depot storage and refuelling) up to the year 2030. In particular, two pathways of high relevance to this timeframe were considered: Steam reforming of Natural Gas, and Electrolysis powered by Grid Electricity (Table 7.1). The study has created cost projections based on the latest developments in energy prices (meaning an oil price over \$100/bbl), which were not foreseen until very recently.

Despite the high assumed oil price, these cost projections are reasonably well aligned to the HFP “Implementation Plan” targets for 2020 (for example, €40/GJ for steam reforming) which were set in a climate of lower oil prices [4.10].



Table 7.1: Projected 2030 hydrogen filling station price scenarios for major early pathways [7.3]

| | Pathway 1 | | Pathway 2 | |
|--------------------------------|-----------------------------------|---|-------------------------|---|
| | Description | Costs (€ ₂₀₀₀ /GJ) | Description | Costs (€ ₂₀₀₀ /GJ) |
| Production | Natural gas steam reforming (SMR) | 37.40 | Electrolysis | 52.52 |
| Transport | Tube Trailer | 6.72 | Tube Trailer | 6.72 |
| Storage | On-site gaseous storage | 5.00 | On-site gaseous storage | 5.00 |
| Cost for the final user | | 49.11 €₂₀₀₀/GJ 5.89 €₂₀₀₀/kg | | 64.24 €₂₀₀₀/GJ 7.70 €₂₀₀₀/kg |

Note that the €₂₀₀₀ unit is a Euro price corrected for inflation to a year 2000 reference

The cost balance between capital purchase and fuelling will be a critical part of the technology adoption equation that is explored in Section 7.5 below. However, in a future likely to be increasingly dominated by issues of greenhouse gas emission and resource usage, it is also important to consider the efficiency of the energy chain (which can be related to greenhouse gas emissions). This part of the study also created efficiency projections for 2030 based on estimated advances in the state of the art in production techniques (Figure 7.2).

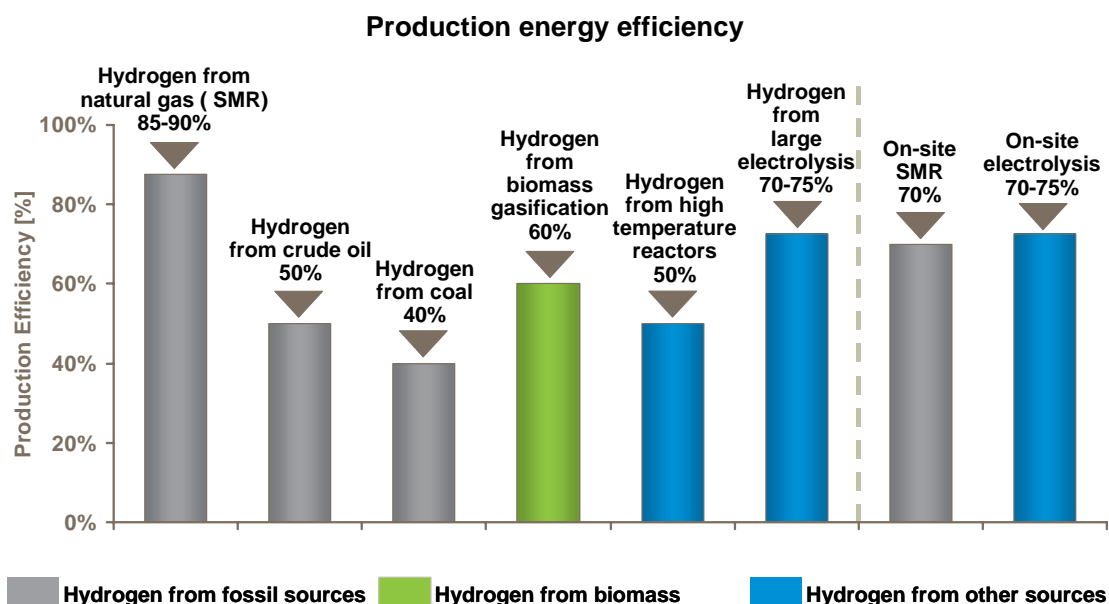


Figure 7.3: Energy chain efficiencies for 2030, primary source to hydrogen fuel [7.3]



7.4 The Tank to User component

The “tank to user” part of the picture is essentially the specific application of the new technology (for example a vehicle or a heat/power system), which is usually sold to a private or commercial buyer as a capital or lease purchase. Most applications have been demonstrated at least as a research prototype today, but future products are likely to continue to improve on these prototypes in terms of performance, efficiency and cost. This part of the project [7.4] therefore looks at the likely evolution of some key applications up to 2030, particularly in respect of the key attributes of their energy efficiency and price. Applications studied include:

- Light and heavy duty road vehicles (cars, buses, trucks)
- Auxiliary and main power for rail, sea and air applications
- Generation and co-generation (heat/power) for domestic, industrial and backup applications

This study used published data from within Roads2HyCom (for example the State of the Art analysis, [4.8]) and other sources, to create projections. In particular, published “learning curve” models for cost reduction with increasing volume, were used to ensure that different data sources were compared or aggregated on a like-for-like basis.

This “Learning Curve” effect has two principal implications:

- **Increases in product volume**, particularly up to around 1000-10000 units, have a strong impact on unit price, as production tooling and engineering costs can be amortised over far more units. This is an important relationship to consider in relation to the role of early markets and civic procurement, as a small early market may not result in enough cost reduction to make the product more broadly attractive (Figure 7.4)
- **Larger units tend to have a lower cost per kilowatt**, as manufacturing more stack plates brings their individual cost down, and the cost of “balance of plant” items does not increase so steeply with size. Again this is an important part of the product desirability relationship, which could not be deduced from a uniform “€/kW” figure (Figure 7.5)

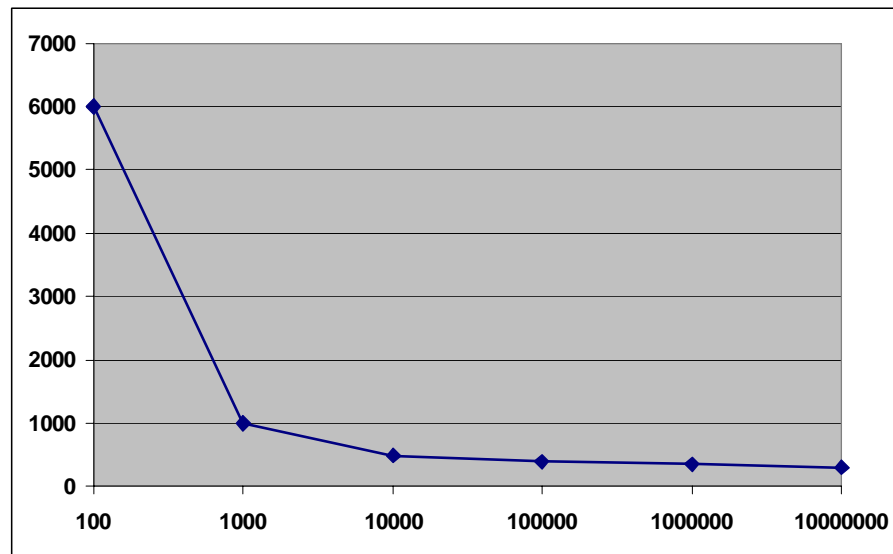


Figure 7.4: Cost / Volume relationship for a PEM fuel cell, from US DoE data [7.4]
Cumulative volume is the horizontal axis, relative cost the vertical

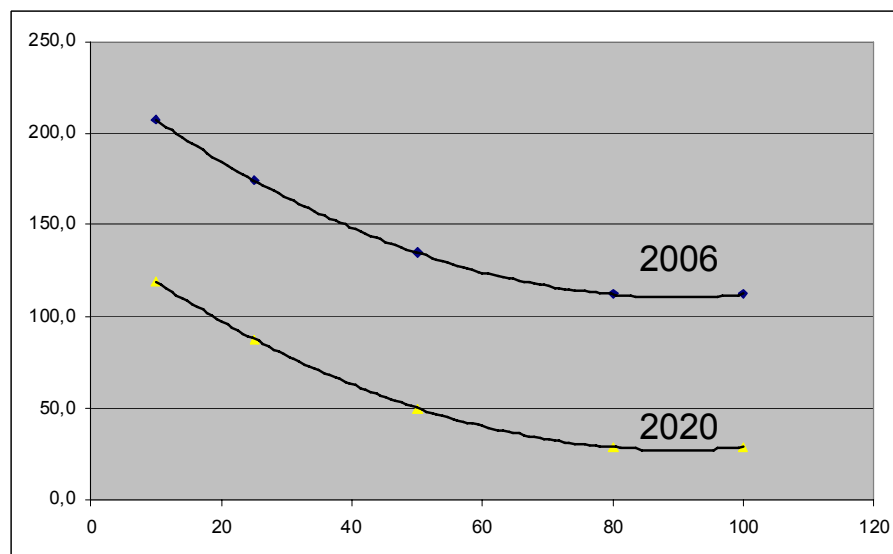


Figure 7.5: Cost / Size relationship for a PEM fuel cell system at 500,000 units per year [7.4]



The outputs of this work formed the basis of the analysis of purchase and fuel costs presented in the next section [7.5]. Broadly speaking, the fuel cell system cost breakdowns (Figure 7.6 and Figure 7.7) are in line with conventionally accepted views. Similar data was created for hydrogen tanks and hydrogen ICEs [7.4].

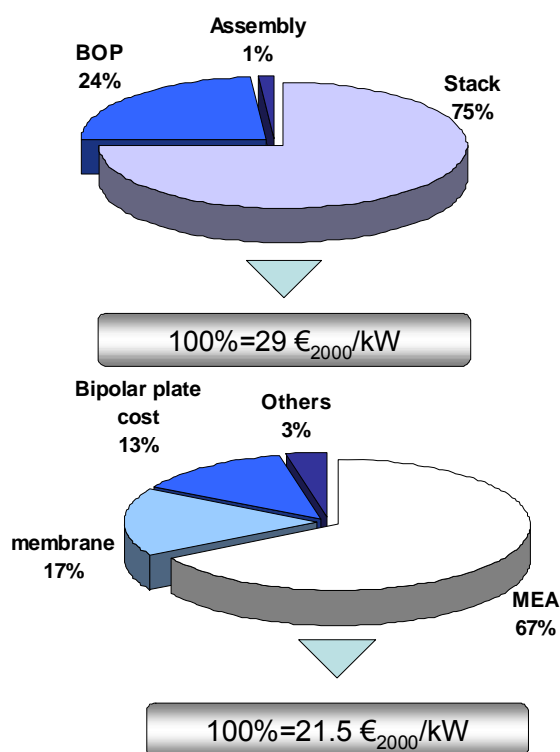


Figure 7.6: Projected 2030 cost breakdown for PEM system and stack for transport applications, assuming high volume production of 500,000 units per year [7.4]

Note that the €₂₀₀₀ unit is a Euro price corrected for inflation to a year 2000 reference

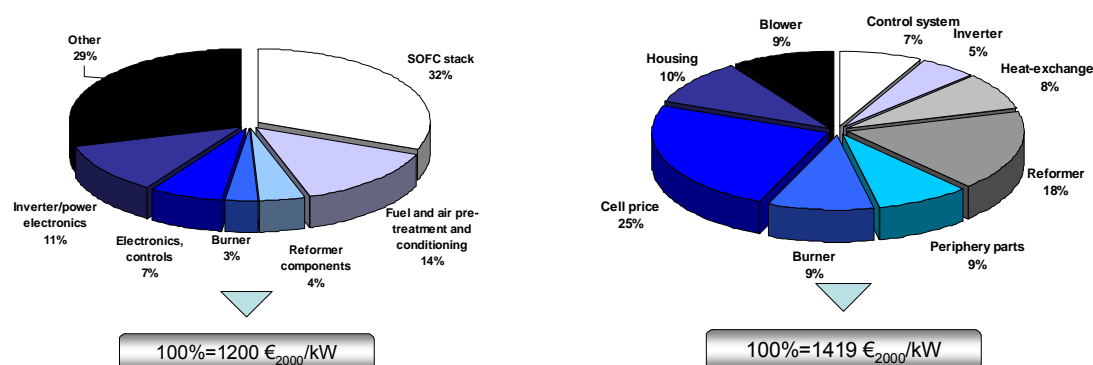


Figure 7.7: Projected 2030 cost breakdown for Industrial SOFC (100-200kW) (left) and MCFC (300 kW), assuming 10,000-100,000 units produced per year [7.4]



Note that the €₂₀₀₀ unit is a Euro price corrected for inflation to a year 2000 reference

A set of consolidated cost results for various 2030 applications is shown in Table 7.2. This data shows some interesting features, for example the significantly higher “cost per kilowatt” of a Stationary sector PEM (compared to one for Transport in equal volumes), arising from its much longer durability requirement and smaller power output (a small unit requires the same balance of plant as a larger one, and uses less stack material, hence less economy of scale in stack manufacture).

Table 7.2: Consolidated 2030 cost data [7.4]

| Applications | Fuel Cell Type | Fuel | Size [kW] | Production Volumes | Cost [€ ₂₀₀₀ /kW] |
|--------------|----------------|-------------|-----------|--------------------|------------------------------|
| Transport | PEM FC | Hydrogen | 25 | 500,000 | 88 |
| | PEM FC | Hydrogen | 80 | 10,000,000 | 22.5 |
| Stationary | PEM FC | Hydrogen | 5 | 10,000,000 | 635 |
| | PEM FC | Hydrogen | 50 | 100,000 | 508 |
| | PEM FC | Natural Gas | 50 | 100,000 | 720 |
| | SOFC | Natural Gas | 1-10 | 100,000 | 1749 |
| | SOFC | Natural Gas | 100-200 | 100,000 | 1200 |
| | MCFC | Natural Gas | 300 | 100,000 | 1419 |

Note that the €₂₀₀₀ unit is a Euro price corrected for inflation to a year 2000 reference

The evolution of competing technologies is also considered, as it is important to recognise that Fuel Cell and Hydrogen technologies must compete with conventional products that will be better than they are today. Examples include:

- Improved fossil-fuelled internal combustion engines (road, rail, sea, air, generator sets)
- Hybrid and electric vehicles (road, rail)
- Sails and kite-sails for commercial vessels (sea)

7.5 Analysis of Gaps, Opportunities and Synergies in Fuel Cells and Hydrogen

7.5.1 Analysis Methodology

Once the overall trajectories by which the technology might develop and start to enter the market are understood, it becomes possible to identify some features of strategic relevance:



- **Gaps**, where predicted or planned advances in the State of the Art may not be wholly sufficient to ensure that a product is attractive to mainstream markets
- **Opportunities**, where economics and the state of the art make market uptake look particularly attractive
- **Synergies**, meaning situations where a technology advance or market transformation in one sector has a beneficial effect in others

Most potential Fuel Cell and Hydrogen applications have been demonstrated, at least in prototype form; but the ability to produce them at acceptable cost remains a key challenge, as described in Chapter 4. Likewise most of the energy chains have been demonstrated but not yet up-scaled to realise cost economies. Therefore the central pillar of the analysis technique employed [7.5], was the synthesis of a relationship between the capital cost of the application, and the cost of the fuel. As the ownership cost includes both elements, it follows that the sum of the two over the product's life or period of ownership needs to be lower than a competing benchmark in order to attract buyers.

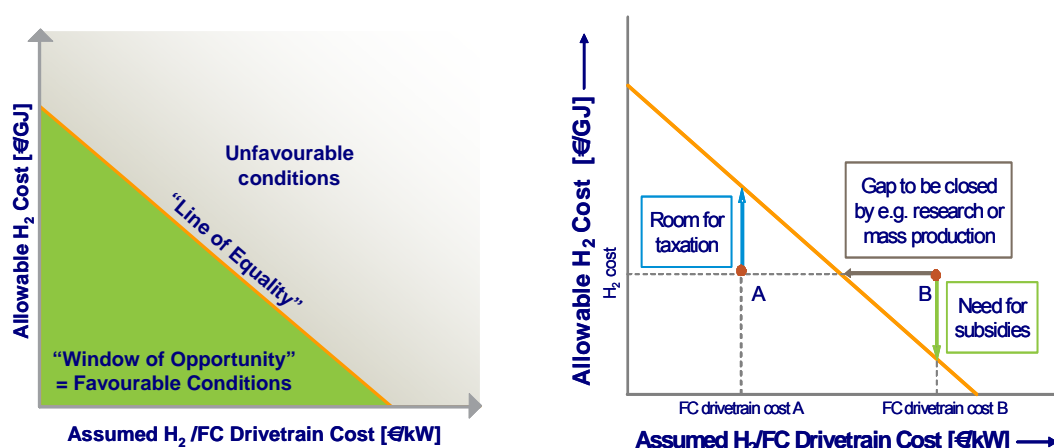


Figure 7.8: Cost trade-off methodology [7.5]

Case studies were created for sixteen transport and seven stationary power applications, using the energy chain and technology evolution data from the studies described above [7.3, 7.4] and other sources [7.5].

Capital cost is a major challenge for applications that compete with well-established technologies like internal combustion engines (which are cheap to manufacture on a price-per-kW basis due to mature processes and cheap materials) and industrial electric drives. Figure 7.9 shows some examples from the analysis, for the case of Passenger cars and Forklift trucks. Interesting points that emerge are:

- **The gradient of the relationship between acceptable system and fuel costs reflects the duty cycle:** Applications such as goods handling vehicles that enjoy heavy utilisation are relatively more sensitive to fuel price, less to



capital cost; low utilisation applications like the passenger car are much more purchase price sensitive

- **Some goods-handling applications, especially those with high utilisation, become attractive at relatively high fuel cell system costs (over €1000/kW).** This finding is expected, and is consistent with early market activities noted in the Technology Watch study [4.15]

However, it is established that there are strong relationships between product volume, fuel cell size and price, as described in the previous section. It is therefore necessary to re-examine the results of Figure 7.9 in comparison to projected costs for each application.

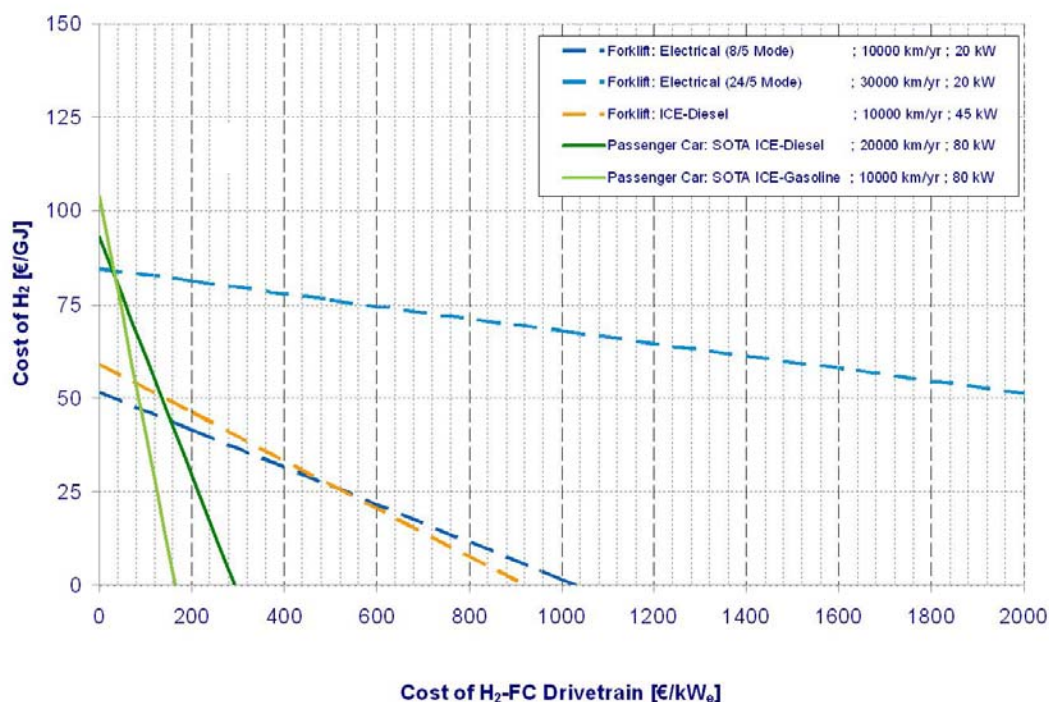


Figure 7.9: Cost trade-off against some selected transport applications [7.5]

7.5.2 Goods Handling

Figure 7.10 shows the Forklift data with today's SOTA and estimated 2030 prices [7.3, 7.4] for 1% and 10% of the market for this type of vehicle. As can be seen, the fuel cell option appears attractive for a highly utilised vehicle (24 hour warehouse) even at the lower volumes, though with a strong sensitivity to hydrogen price (which could initially be higher for very low supply volumes).

However, in the case of the forklift truck, the analysis also shows that Diesel and Electric technologies are not likely to be displaced from less utilised vehicles on the basis of economy of scale from just within this sector. Economies driven by uptake in road vehicles could of course change this picture.

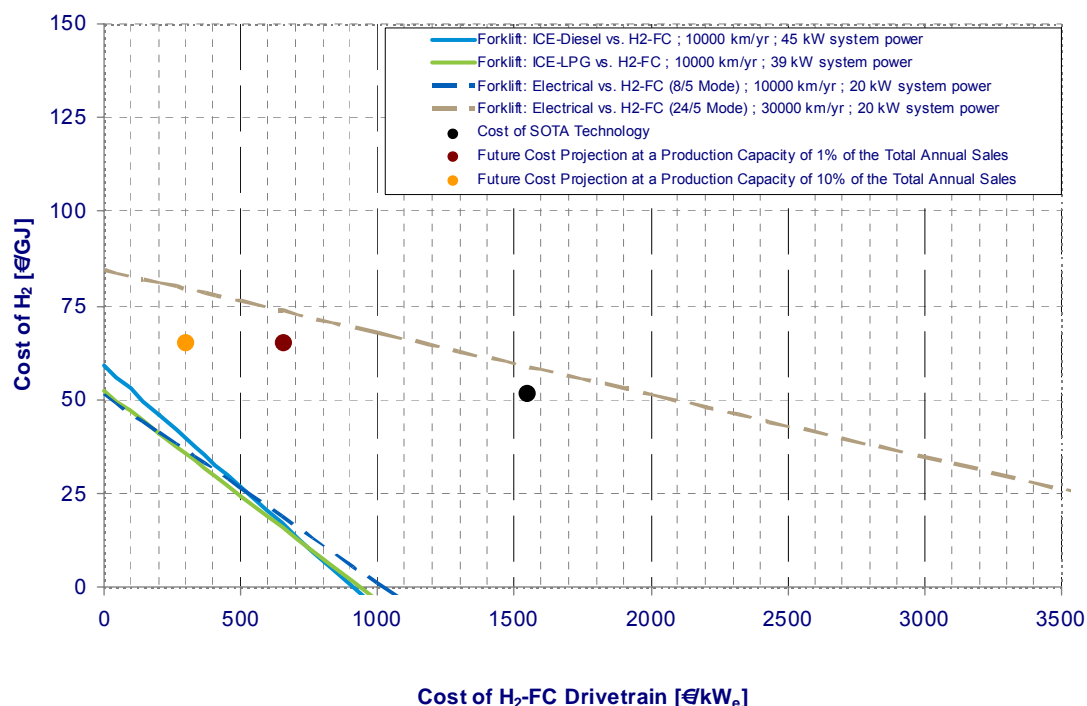


Figure 7.10: Competitive position for 2030 Fuel Cell forklift [7.5]

7.5.3 Road Transport

Figure 7.11 shows the same analysis for the case of the passenger car. The analysis shows current “in-production” state-of-the-art with respect to cost (data point shown in black), indicating a position that is far from competitive. However, Figure 7.11 also shows the impact of projected progress in the state of the art [7.3, 7.4] and economies of scale [7.5]. The result is much more promising, with some market appeal (for higher-mileage Diesel buyers) at just 1% penetration, while volumes over 10% penetration could prove sufficient to make the Fuel Cell car universally attractive; a position that could be further reinforced with more stringent environmental taxation [7.5]. Of course, achieving this in practise requires technological progress in underlying unit cost and realising low cost manufacture, to achieve what is projected. As the ability to manufacture fuel cells at such low costs remains unproven, it could be argued that reality may lie between one of these cases and the other. This means that research to support the realisation of low costs is of crucial importance. Furthermore, as civic and public procurement initiatives alone do not have the capacity to reach even 10% of the market, the implication here is that pioneering fuel cell car manufacturers will be faced with a significant period of loss-leadership while volumes build. Here the cost of hydrogen is less sensitive, but other factors such as penalties for poor environmental performance could bring the tipping-point to a lower penetration.

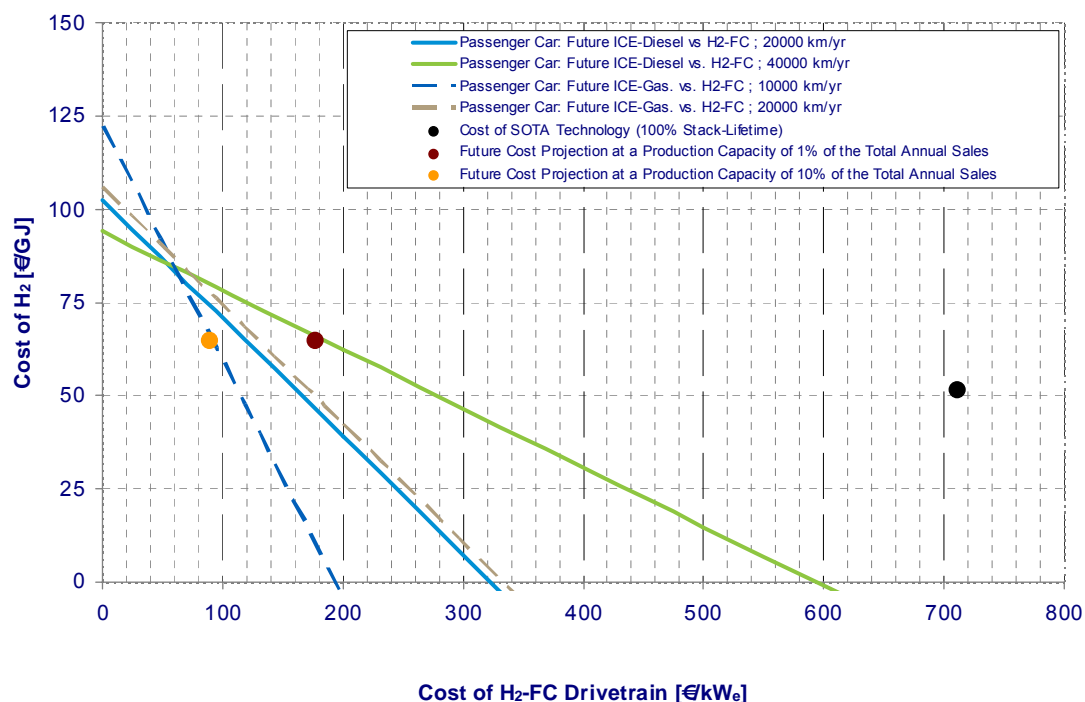


Figure 7.11: Competitive position for 2030 car, known and projected SOTA [7.5]

The analysis [7.5] also looked at other transport applications: light trucks in urban usage showed strong promise, as shown in Figure 7.12, requiring smaller shifts in SOTA cost or taxation to make them attractive. It should be noted that this is a very conservative, capital cost driven sector that has yet to adopt much new technology, although corporate fleet users (particularly those with a tendency to government ownership, such as postal services) could be significant early adopters. Buses, being built in lower volumes, require much greater progress and market penetration to approach viability, although they have much greater potential to benefit from civic initiatives, and their high fuel usage means that the right incentive package for fuel cost could tip the balance more in their favour.

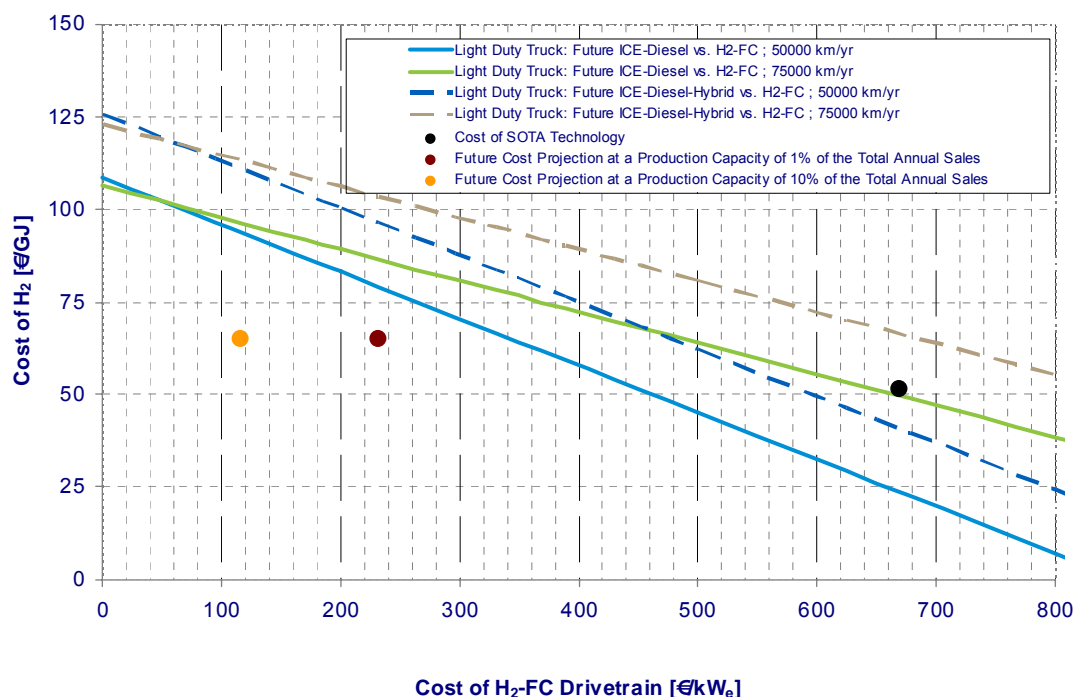


Figure 7.12: Competitive position for 2030 light duty trucks, known and projected SOTA [7.5]

7.5.4 Stationary Combined Heat-Power

The analysis follows a slightly different form for the stationary sector, where the new Fuel Cell technology shares its fuel (Natural Gas) with the incumbent technology. Here the trade-off line runs across the other diagonal of the graph (Figure 7.13), meaning that a high gas price favours the more efficient Fuel Cell

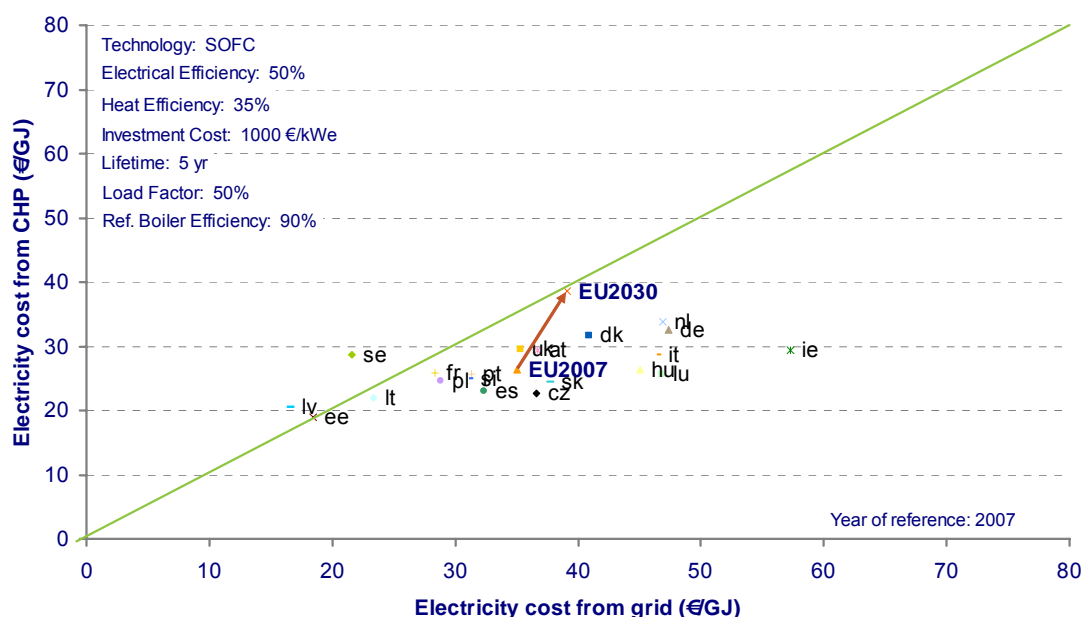


Figure 7.13: Cost trade-off for Industrial CHP [7.5]

The analysis indicates that the Fuel Cell becomes attractive for CHP at between €1000 and €2000/kW(e), depending on the system chosen and gas price. Again, this is consistent with observations from Chapter 4, with the start of increasing market interest corresponding to quoted prices just over €2000/kW for a new generation of products. The local CHP market exists because of the difference between gas and electricity prices, which varies by country and from domestic to industrial applications. The analysis (Figure 7.13 above) shows that most EU-27 countries currently enjoy favourable conditions for CHP; however, the rate at which electricity and gas prices rise is critical. If gas (a fossil resource that is being depleted in Europe) rises in price faster than Electricity (which will increasingly be derived from Renewables whose “fuel” is free), the window of opportunity for CHP might close. The project’s own chosen 2030 price scenario indicates that, for example, a Molten Carbonate system (at circa €1400/kW installed capital cost) becomes marginal by 2030. This means that progress in reducing capital costs must allow the environmental benefits of CHP to be realised soon.

The aggregation of these case studies was also used to estimate the maximum CO₂ abatement potential of the applications (Figure 7.14). A “best case” was based on the HyWays 2030 Hydrogen mix [3.3], which relies on much increased use of wind energy / electrolysis, carbon-captured fossil fuels and biomass. As discussed in Chapter 5, there appears to be a risk that competition from the demands of the electricity grid and bio-fuel manufacture, plus the immaturity of carbon capture, will mean that such a mix could not be supported; even though the potential for it to do so exists.

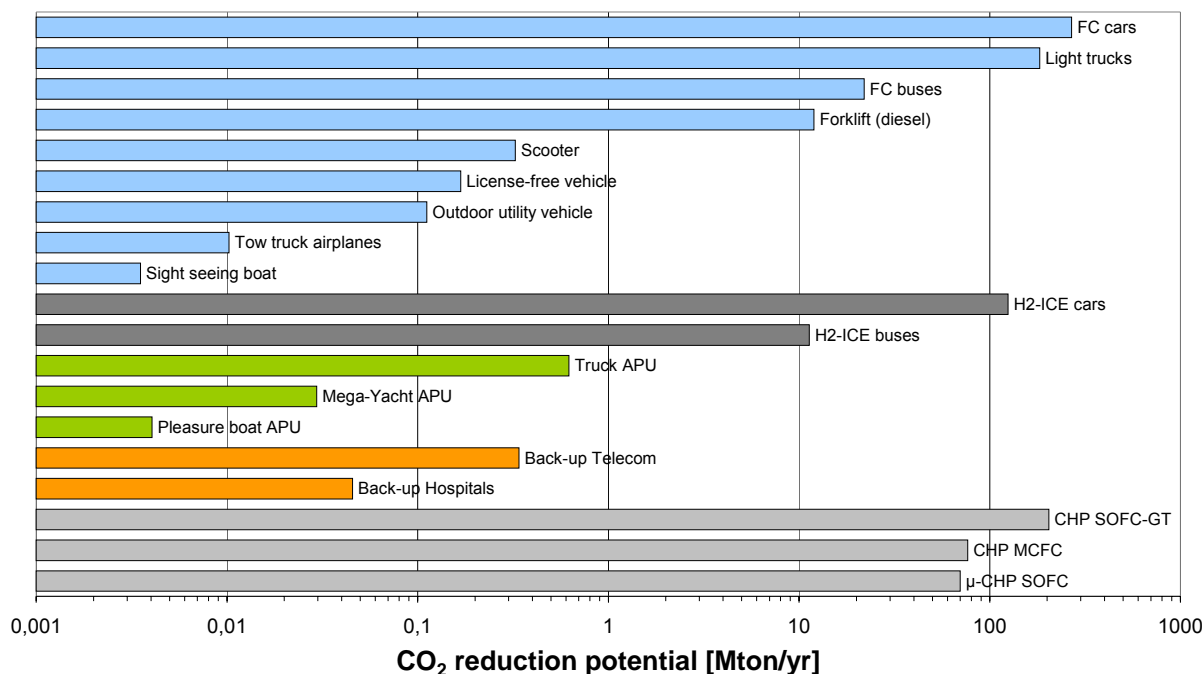


Figure 7.14: Maximum abatement potential of applications – HyWays mix [7.5]

7.5.5 Opportunities for Fuel Cells and Hydrogen

On the basis of cost alone, key opportunities appear well aligned with developments in early markets identified in Chapter 4 and the Technology Watch [4.15]:

- **Systems with batteries that have limited capacity:** Back-up for telecom and Forklifts in 24/5 or 24/7 are near term markets; extending the range of electric vehicles and substituting the combustion-engine of plug-in Hybrids could develop as markets in the longer term if aggregated stack demand creates attractive prices

On the basis of environmental potential, the picture depends on application and energy chain:

- **The high temperature Fuel Cell for CHP** offers superior efficiency in its use of Natural Gas in domestic and industrial sizes, with potential for major overall impact, but its window of opportunity will be governed by the future trajectory of electricity and gas prices
- **Mainstream road transport applications** offer the greatest overall potential, but require hydrogen production from renewable sources to fully realise it, and require technology progress and a degree of loss-leadership until a high market penetration brings the cost down



7.5.6 Gaps in the current or anticipated State of the Art

From the preceding analysis, the following appear to be the most significant potential gaps; broadly these findings are in line with other evidence presented in Chapter 4:

- **Cost:** The analysis has shown that, until very high sales penetrations are reached, mass-production of a few early products does not alone bridge the “cost gap”. While it has been confirmed that many applications become attractive if cost targets projected in the Implementation Plan [4.10] and HyWays roadmap [3.3] are achieved, it is clear that further advances in the State of the Art are desired, both for Fuel Cells and Hydrogen storage; the considerable effort, from research to training and supply chain integration should not be underestimated, especially for the most capital cost sensitive applications. The cost of hydrogen as a fuel is not such a high risk technically, but the question of its taxation (or exemption) needs to be addressed pragmatically, as does the need to implement attractive pricing for initial, low levels of supply
- **Lifetime:** The analysis highlights the importance of achieving long lifetime from the costly Fuel Cell systems in order to sustain a business case
- **Infrastructure:** The analysis assumes that production and distribution infrastructures allow the fuel price scenario to be realised; failure of build-up is a risk in terms of high fuel prices and user inconvenience
- **Advances in competing alternatives:** In particular, advances in battery technology could erode the storage and range advantages enjoyed by Hydrogen fuelled transport; given that the Electricity – Battery – Propulsion energy chain is twice as efficient as Electricity – Hydrogen – Propulsion, this is a critical future unknown; although as yet there is no demonstrated evidence of battery technology closing the gap sufficiently, advances in cell surface nano-technology could provide a breakthrough by the 2030 timeframe. The same phenomenon is seen in the “window of opportunity” competition between CHP and the development of a mature, low cost renewable electricity supply combined with energy-saving measures

7.5.7 Technology and Application synergies

Synergies are important because they can transform the business-case for the new technology. Some synergies that have been postulated from the analysis performed are:

- **Achieving high volume of generic components:** The analysis has shown that low volume niche markets do not leverage enough economy of scale to reach mass-market targets. Such early markets are undoubtedly helpful in refining the product and its production processes, but the commercial decision to go ahead with wider application in a field like Transport requires a larger critical mass of applications based on a common family of components
- **Hydrogen infrastructure build-up:** There is a real opportunity to leverage the demand created by each application as it enters the “mass market” in its



sector. The analysis indicates that Fuel Cell buses can be a starting point for the hydrogen filling stations, especially as this application enjoys significant civic support (Chapter 6). This infrastructure can then grow to support other “captive” fleets of vehicles (taxis, municipal service vehicles) operating from the same point. From here, an extended network can begin to attract privately owned or commercial Niche applications (License-free vehicles; Utility vehicles) with limited operating range; then more mainstream Passenger vehicles and light trucks as the technology, infrastructure and availability of more de-carbonised hydrogen supply provide the conditions for uptake. This issue is also explored by the HyWays project [3.3].

- **Electricity and Hydrogen in Transport:** Recent advances in battery technology have brought the prospect of the “plug-in Hybrid” vehicle, which uses electric drive for short journeys and a down-sized combustion engine for longer journeys. This model is well suited to family passenger cars; following this model, a hybrid Hydrogen-Electric vehicle could use plug-in power at high efficiency for short journeys, and call upon the Fuel Cell as a range extender on longer journeys. In this way the Hydrogen infrastructure can be focused upon trunk routes and key nodes where the civic captive fleets described above will have provided a seed. Interestingly a secondary synergy might arise whereby the increased electricity demand can be met by small scale fuel-cell CHP (with mutual improvement of business case); but conversely a critical mass of vehicle battery capacity plugged in to the grid might reduce the demand for Hydrogen as an energy buffer as suggested in Chapter 5.
- **Tri-generation:** The potential medium term attractiveness of CHP applications (e.g. SOFC and MCFC) brings the possibility of extending the reforming capability of the CHP system to produce excess hydrogen for refuelling, at either domestic or local industrial scale; again, this provides an alternative technical pathway round the infrastructure problem while using the some of the heat from the CHP system in a higher-value way
- **Water production:** For airplane application and perhaps remote desert power generation, water production from a fuel cell APU is an additional benefit in terms of weight (aircraft) or convenience (desert)

The detail investigation of these synergies would be very case-specific, but generic measures that must be pursued to take advantage of them include:

- **Supporting research** on the cost and part-count reduction of all components, and the development of cheaper materials, especially for electrode catalysts and hydrogen storage systems; also on implementation of reliable, robust, durable fuel cells (with improved operational window) into early markets
- **Development of policies** that support market development by incentivising sustainable energy production, industrial development in the clean-tech sector, low energy use, improved air quality and reduced oil dependence

These issues are discussed in the following chapters.



8. Conclusions for the Research Agenda

8.1 Why technology development will continue to be important

It is not always the case that improvements in a technology are required in order for it to succeed in the marketplace – other factors, usually market inertia combined with an insufficiently compelling business case, can be the main barrier.

However, in the case of Fuel Cells and Hydrogen, technological advances that are yet to be realised, will play a crucial role in determining the success of these technologies. It is difficult to generalise in a way that covers every application, but the project has tended to find that the commonly held expert perceptions of technology challenges still hold true:

- **Cost:** As reported in previous chapters, latest projections (essentially, what a Fuel Cell system would cost if mass-produced) are encouraging, but a significant detail-level research effort, focused on design-for-manufacture and production techniques, is required to ensure that these projections are turned into reality. This applies in any sector, but most in sectors with high volume and price sensitivity such as road transport and domestic heat-power
- **Durability:** Again, recent progress discussed above has been encouraging, but continued research efforts are needed to deliver further improvements that can be realised in a volume-manufactured product that is robust to a wide range of environmental conditions, accidental misuse and malfunction
- **Energy storage:** Moving toward the exceptional energy-density offered by today's liquid fuels in transport applications, is a challenge for both hydrogen storage and electrical storage; the superior efficiency of their power converting devices (fuel cells, electric motors) only partly compensates for the deficit. The State of the Art in both hydrogen and electricity storage is "bulky and very costly"; the race between the two will be a defining technological battle, but progress in both can be complementary as many fuel cell transport applications will use batteries to recycle braking energy
- **Infrastructure:** Although industrial hydrogen infrastructure is mature, it has achieved that maturity in today's industrial economic context. Detail research effort on efficient and safe production (including production systems that synergise with new energy resources and energy grids) and distribution, will be required to support a broader and more publically accessible fuel infrastructure

Finally, all these challenges need to be constantly re-appraised in terms of likely advances in Competitive Benchmarks. It is never safe to assume that incumbent technologies will stagnate; indeed the treat of a revolutionary new technology can have the opposite effect – for example, developments from the incumbent technology like Electric or plug-in Hybrid vehicles, and power generation devices that use sophisticated "bottoming cycles" to recover extra energy from their exhaust.



Research strategy therefore needs to deliver outputs that can remain one step ahead of the competition.

8.2 How Roads2HyCom has created strategic recommendations

8.2.1 The HFP's Implementation Plan

Between 2004 and 2007, members of the European Technology Platform for Hydrogen and Fuel Cells (HFP, [2.4]) created a series of strategic documents to guide the future research and technology development agenda. These documents were:

- **A Strategic Research Agenda** [8.1], which is an outline for future research strategy
- **A Deployment Strategy** [8.2], which examines the broader issues of realising Fuel Cells and Hydrogen commercially
- **An Implementation Plan** [4.10], which prioritises topics for the now-launched Joint Technology Initiative [3.6]

The Roads2HyCom project was initiated just after the creation of the Implementation Plan was started, and five key partners in the project occupied positions in the working groups that created it. Roads2HyCom supplied two sets of feedback to the open consultations on the Implementation Plan [8.3, 8.4] and co-ordinated an independent review of European Commission and US DoE funded research [8.5, 8.6]; though as these were delivered early in the project's life, they were based more on project partners' experience than on new analysis. Nonetheless, both the Implementation Plan and some of the key themes from that early feedback served as guides to the process that followed.

8.2.2 Project Methodology

Roads2HyCom has synthesised a set of strategic research recommendations based on data and analysis collected in the various parts of the project. The synthesis uses mostly information described in Chapters 4 (State of the Art, technology landscape, learning from demonstrations) and 7 (Technology pathways, gaps, opportunities and synergies), but considering also the infrastructural and socio-economic issues (Chapters 5 and 6) that relate to technological need. Key steps in the process were:

- **Creation of a list of Topic Areas**, based on the project's generic Technology Tree (Figure 4.7) and project expert input
- **Population of that list of Topic Areas with short topic summaries**, collations of time-linked Milestones from existing worldwide strategy papers, collations of published numerical Technical targets from similar sources, and suggested Recommendations (in terms of development of those Milestones and Targets) developed by the Roads2HyCom team



- **Organisation of a peer review workshop** of project members and invited external experts, to develop this document [8.7]
- **Development of a two dimensional prioritisation process** (technical need, societal importance)[8.8], based on the above recommendations and the outputs of the Gaps, Opportunities and Synergies analysis described in Chapter 7 [7.5]
- **Validation and refinement of this Prioritisation at a second workshop** and by peer review within the project

8.3 Research Topics and Milestones

This study divided research topics into five main chapters: hydrogen production, hydrogen storage, distribution and refuelling, hydrogen energy converters, and cross cutting issues [8.7]. For each, the study developed tables with an overview of international milestones, technical targets and consequent research recommendations, the latter being time-divided into 2015, 2020, and 2030 and beyond. It is impossible to exhaustively summarise this work, but in overview the following can be said about each research topic:

- **Hydrogen production:** As carbon-free fuel, hydrogen has the potential for a carbon-free energy cycle provided it is produced without the emission of CO₂. This is not happening at present, as most Hydrogen is currently produced from hydrocarbons. Carbon-capture, electrolysis of water with electricity from carbon-free sources, or direct production of hydrogen from such sources, creates a CO₂-free hydrogen fuel. Main research topics are industrialisation of unproven or laboratory-scale processes, and reduction of costs of equipment and electricity; while as an interim measure, reducing the carbon footprint of existing industrial processes through efficiency improvement and realisation of carbon capture is desirable. There are many potential routes, with the only “certainty” being that, in a future with more scarce energy resources, multiple routes are likely to be required.
- **Hydrogen storage:** Efficient storage with high energy density plays a key role for hydrogen application, especially in the case of onboard storage in vehicles. Storage methods, such as compressed gas, cryogenic liquid, and in compounds, are analyzed. Main research topics are focusing on the increase of gravimetric and volumetric energy density and reduction of costs of storage systems. This will prove challenging, as the commonly used gaseous and liquid technologies are constrained by laws-of-physics issues, and the best known state-of-the-art is around 5 times more expensive and 2 times more heavy than desired. Reduction of fuel requirement, through lighter and more efficient vehicles, must play a part in solving this challenge.
- **Distribution and refuelling:** Hydrogen is distributed in compressed or liquid form in trailers by road, rail or ship. For the containers the same research issues as for already described tank systems in general are applicable. The use of pipelines to distribute hydrogen gas or mixtures with natural gas offers



an interesting alternative. In filling stations, reduction of costs is the main aim of research.

- **Hydrogen energy converters:** As carbon free fuel, hydrogen can be used with low or no emissions in turbines, internal combustion engines, or fuel cells; some forms of fuel cell can use existing natural gas supplies or other hydrocarbons as a fuel. The usage of hydrogen as an energy carrier, and/or the fuel cell as an energy converter, is discussed for stationary, portable, and automotive applications. Fuel cells promise clean energy conversion, without emissions, at high efficiency rates; though costs and weight are high. Research recommendations focus on realising recent improvements at prototype level in lower-cost, reliable, mass-produced products. In the stationary sector (particularly uninterruptible power and co-generation at the “kilowatt to megawatt” scale), some of these products are approaching full commercialisation (meaning products that are profitable along the value chain, sold in volumes that are significant in the sector) in the next decade – the research agenda needs to ensure that the first generation is successful and the second generation is even better. Commercialising in the transport sector is more challenging, with ultimately greater rewards but the need to realise high product volumes before costs can be reduced – so the research agenda needs to support extended demonstration activity to realise these ambitions.
- **Cross-cutting issues:** Apart from technical issues, a variety of socio-economic questions have to be addressed. Political and financial decisions, e.g. about taxes play an important role in the implementation of hydrogen and fuel cells into the market. Safety, standards and regulation have to support technical development. And the education agenda, at all levels, has to provide the skills required in business development, product development, fuel supply and in-field operation. Studies within the Roads2HyCom project deliver recommendations on many of these issues, but further work will be required as fuel cells and hydrogen are realised in a sustainable energy economy.

8.4 Roads2HyCom’s strategic recommendations

As the final step, a prioritisation exercise was conducted to place these recommendations on axes of importance and research effort [8.8]. Key steps in the prioritisation were:

- **Collation of common, recurring or similar themes** from each sub-set of the five topics described above – the idea being to reduce a large number of detailed research requirements to a more manageable number of generic ones
- **Creation of axis definitions** for two-dimensional matrices of importance and difficulty – in general, the Importance axis was used to measure the significance of the research topic in bringing about mass-market uptake of the new technologies, the Difficulty axis was used to indicate the degree of



cohesive effort needed to achieve a result which is satisfactory for that mass uptake

- **Placement of the collated research topics onto the axes**, by a project expert group but using the results of the projects' studies to provide justification – the final positioning of the topics is the result of consensus, not calculation, but frequent use was made of project results in resolving where to place each item

In interpreting such a prioritization, it is important to understand that there is no absolute implication that one topic is more worthy than another; indeed, it is more helpful to think of the prioritization diagram as identifying what kind of action may be most effective at achieving the desired outcome. This is illustrated in Figure 8.1. As always, it is vital that the different support mechanisms tie together, especially the pipeline from basic research to product commercialisation.

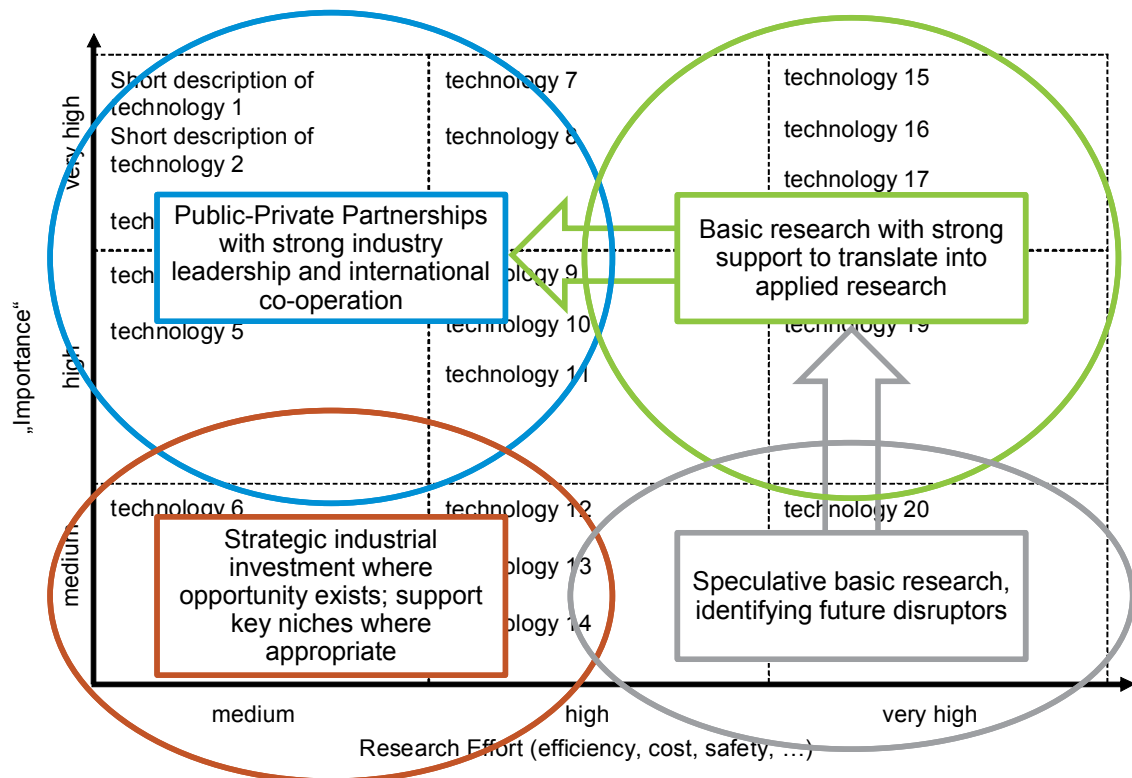


Figure 8.1: Prioritization matrix and appropriate instruments [8.8]



8.4.1 Hydrogen Production

As described in Chapters 5 and 9, Roads2HyCom has performed a number of studies relating to the current and future supply of hydrogen. High-level critical issues are the build-up of a useable infrastructure, fuel cost, and the availability of low carbon energy sources relative to other demands such as de-carbonising the electricity grid.

It is likely that, in the early stages of infrastructure build-up, small reformers and electrolyzers will provide hydrogen for small fleets alongside existing industrially produced hydrogen. The next stage may be mid-sized community systems and large centralised hydrogen production facilities with fully developed truck delivery systems for short distances and pipeline delivery for long distances. As markets grow, Carbon Capture and Storage (CCS) and advanced direct conversion methods using photolytic renewable and nuclear technologies will be commercialised. It is therefore necessary that the research agenda should address these topics as the technologies become required for an infrastructure build-up. Challenges that need to be addressed are production cost, low initial demand, CO₂ emissions of current technologies, and the long-term need for a new generation of advanced production technologies increasingly based on fully sustainable energy sources.

Carbon capture and storage (CCS) is identified as an area of high effort and priority, as it has the potential to supply significant quantities of hydrogen (and of course grid electricity) using coal and gas resources available in Europe, while other studies within the project (Chapter 5) have expressed concern that progress is insufficient to meet future demand. Alongside it are a number of improvements in electrolyser-based technologies that will improve the economic equation in fiscally challenging conditions such as peak-logging production from intermittent renewables. In the near term, water electrolysis offers scope for improved effectiveness through higher temperatures and pressures, up-scaling and improved plant durability. For all these technologies, a flow from basic research (materials science, surface chemistry, geology, socio-economics) through to applied research and up-scaling of pilot projects, is essential.

For longer term research, more advanced production technologies such as biological methods, nuclear (or solar) thermochemical water-splitting, photo-electrolysis and photo-biological processes could be a source of disruptive breakthrough. Many of these technologies are at a relatively early stage of development, with economic and practical issues needing to be solved. For these technologies, support instruments need to incubate and identify successful disruptive technologies that can migrate upwards in importance once their credentials are more established.

At the industrial end of the research scale, development needs to continue regarding steam reforming, for greater process efficiency, lower operating cost and reduced carbon footprint. For all hydrogen production processes, there is a need for significant improvement in plant efficiencies, for reduced capital costs and for better reliability and operating flexibility as they approach large-scale reality.

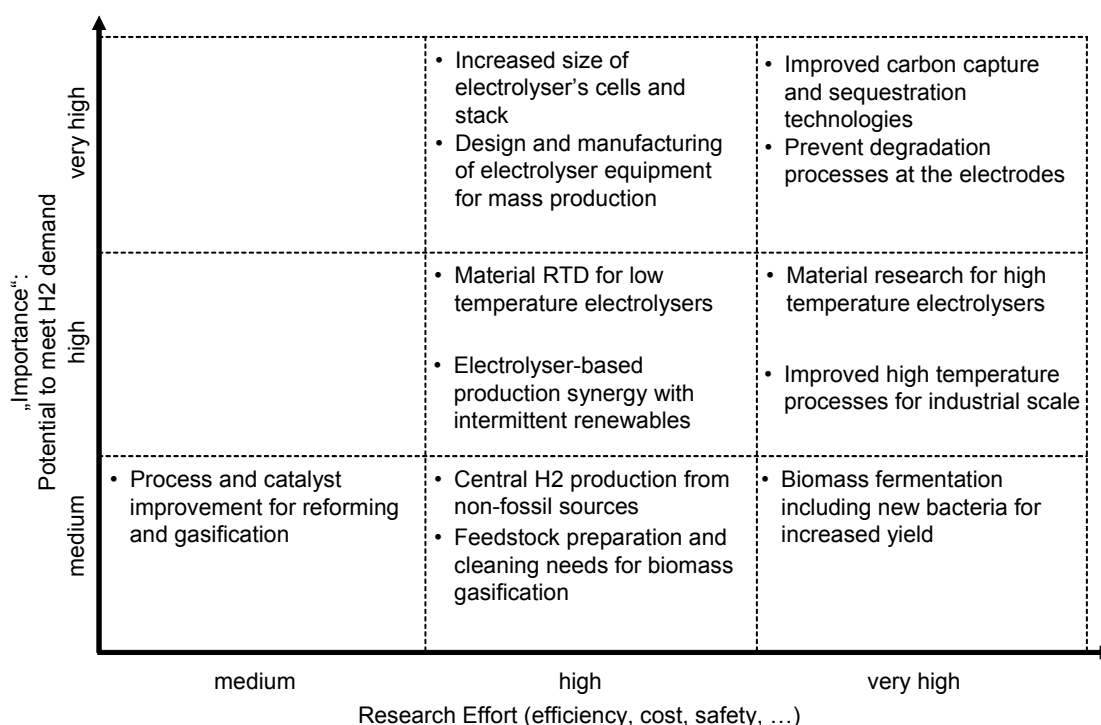


Figure 8.2: Prioritization matrix for Hydrogen production [8.8]

8.4.2 Distribution, Refuelling and Storage

The topics of Storage, Distribution and Refuelling all contain key issues for the widespread use of hydrogen, as described above in Chapters 4, 5 and 7.

Storage, especially in a vehicle or portable device, has been identified as a critical issue where there is a lack of a clear visible route to a mass-market solution (Chapter 4). To improve its very low volumetric energy density, hydrogen is stored as either a compressed gas at high pressures, as a liquid at very low temperatures or in solid storage systems as a physical or chemical compound. All of these storage methods involve high technical effort and sophisticated storage systems. The highest research effort and highest impact is expected from the reduction of weight, volume and costs of the storage systems, and it is vital that the research pipeline delivers these improvements, feeding incremental gains and more disruptive breakthroughs into successive generations of demonstration and early-adopter product.

Compressed storage of hydrogen at pressures between 350 bar and 900 bar in gas cylinders made of steel, aluminium, carbon and compounds allows moderate storage densities in relatively simple storage systems that are nearest to mass-markets. However, compression work plays a significant role in the energy and carbon footprints of compressed hydrogen, so applied research must focus on its reduction through use of compression techniques that approach thermodynamic ideals. For the next generation of tanks themselves, key issues of research are material choice, component dimensioning and safety of the storage systems.

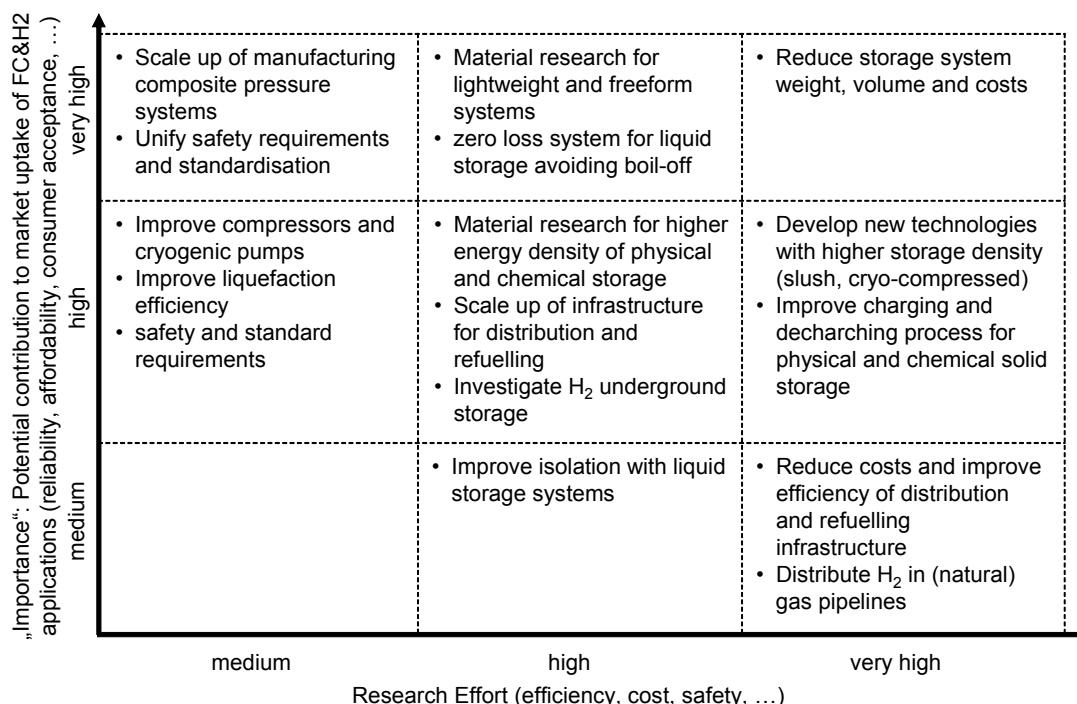


Figure 8.3: Prioritization Matrix for Storage, Distribution and Refuelling [8.8]

Liquid storage of hydrogen at -253°C allows higher energy densities in applications where boil-off is not a limiting factor (implying more frequent refuelling). For applied research (on a similar note to the compressed technologies described above), liquefaction work has to be reduced through adoption of more energy-efficient processes, while for the next generation of tank, key issues of applied research are material choice, component dimensioning and shape, and affordable active technologies to reduce boil-off.

While these two (mature) technologies exhibit storage densities that are limited by the physical state of hydrogen (compressed gas or liquid, respectively), solid storage of hydrogen holds promise for higher energy densities and increased safety. As solid systems migrate towards real applications, conditions for charging and discharging of the systems (pressure, temperature and time) are crucial issues of research.

For distribution and refuelling, scale up of the infrastructure requires a high degree of co-operation between actors, in terms of both the creation of capital-intensive infrastructure and the setting of effective standards. This is a major long-term challenge for the public-private partnership model, the key driver being more economics than technology.

8.4.3 Applications

Figure 8.4 shows the results of the prioritised matrix for Transport Applications, while Figure 8.5 shows the same matrix for Stationary.

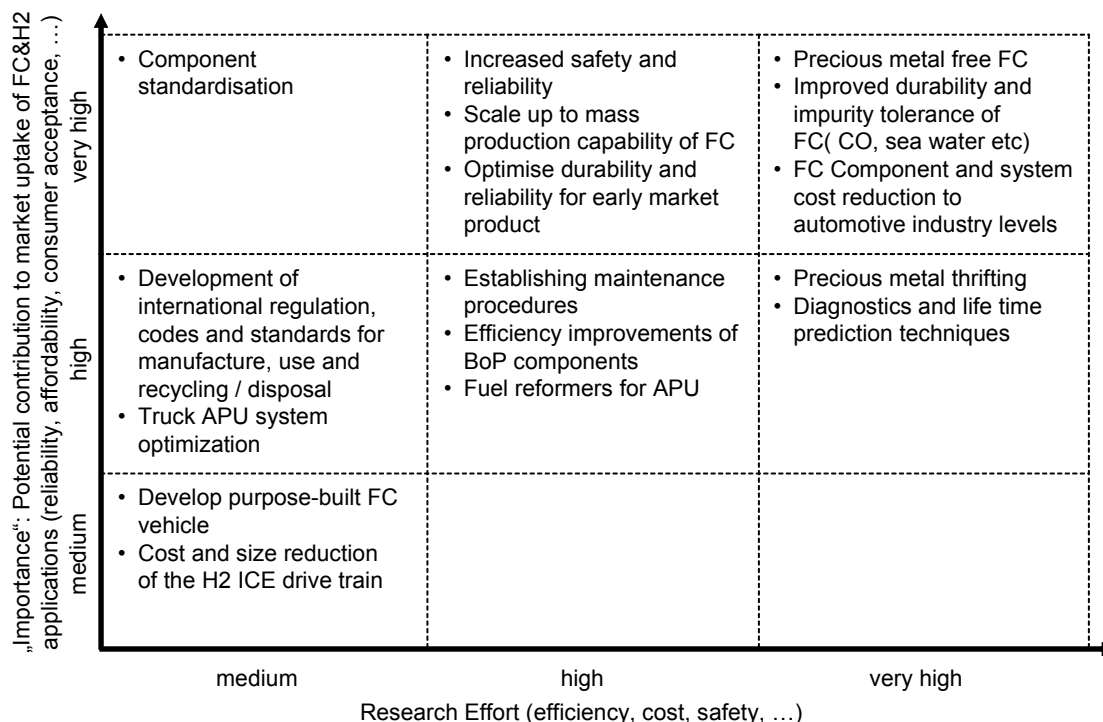


Figure 8.4: Prioritisation Matrix for Transport applications (above) [8.8]

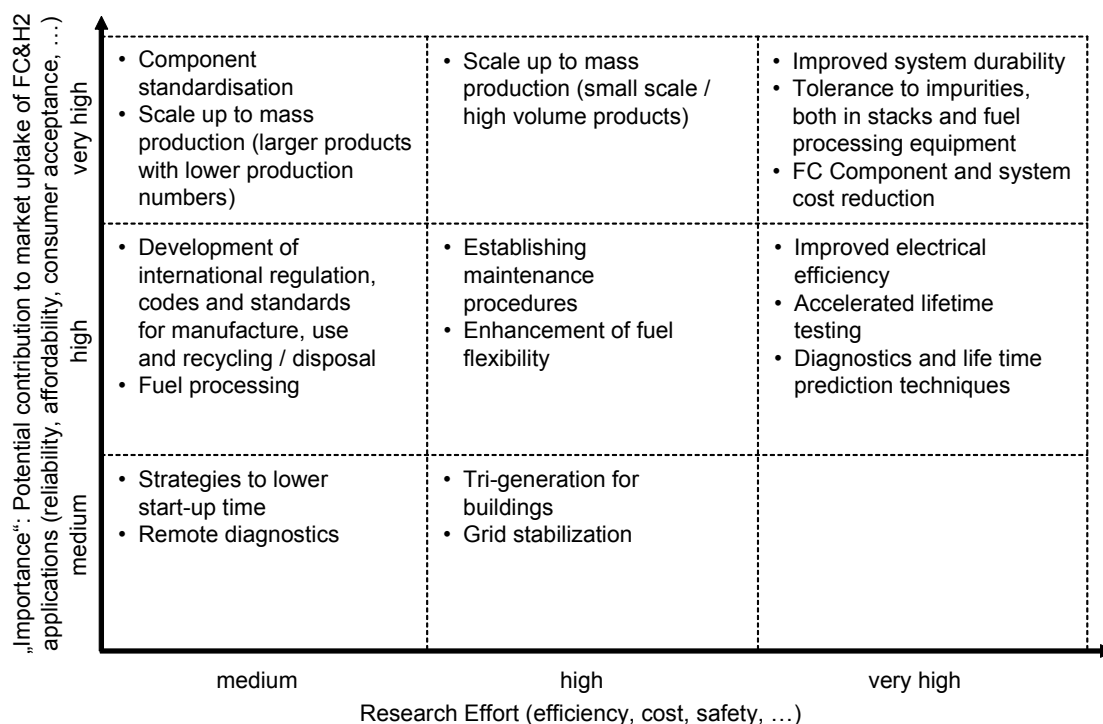


Figure 8.5: Prioritisation Matrix for Stationary applications [8.8]



There are many areas of similarity, so it is worth considering both together:

- Cost remains a critical issue for both types of application, despite the significant progress highlighted in Chapter 4. The analysis of Chapter 7 indicates that the current State of the Art, projected forward in terms of progress and increasing product volumes, remains challenging for early market uptake in Transport applications. For this reason, topics that address cost through better system integration and the thrifting or deletion of costly materials are ranked as highly important – as this will require basic research ideas to be brought through to product, these topics are also ranked as very high difficulty
- As highlighted by some recent demonstrations (Chapter 4), tolerance of impurities remains a key challenge, as fuel cell poisoning has costly consequences. Again, dealing with it is critical to mass uptake, and requires basic research at cell level to be translated to a market-ready product, hence the topic is rated “very high” on both axes
- Realising reliable, safe products manufactured from mass-production processes (not as prototypes) remains critical to early uptake, as there is absolutely no industry experience of mass-produced product in service in either transport or stationary applications. Significant progress by leading players, as reported in Chapter 4, indicates that the “high” category for research effort is generally appropriate, although the challenge of production process scale-up is less severe for larger devices that would be manufactured using batch processes
- Standardisation of components, and development of international standards, remain important to allow both sectors to develop higher volumes, although as the knowledge exists to do both, they are deemed appropriate of more moderate research effort
- Maintenance and diagnostics are important enablers to sustain the growth of early markets. The relative lack of field experience means that a high effort is required to realise trustworthy processes; topics such as smart diagnosis and accelerated lifetime testing require a fundamental understanding of the underlying scientific processes, indicating the highest category of effort

8.4.4 Cross-cutting issues

The challenge of introducing Fuel Cells and Hydrogen are magnified by three factors: the relative immaturity of the technologies, the need for a new fuel infrastructure (except for stationary applications fuelled by natural gas), and the strengths (low cost, familiarity) of incumbent alternatives. The socio-economic dimension remains important, and the technological research agenda needs to recognise the need to continue to forge links with socio-economic research.

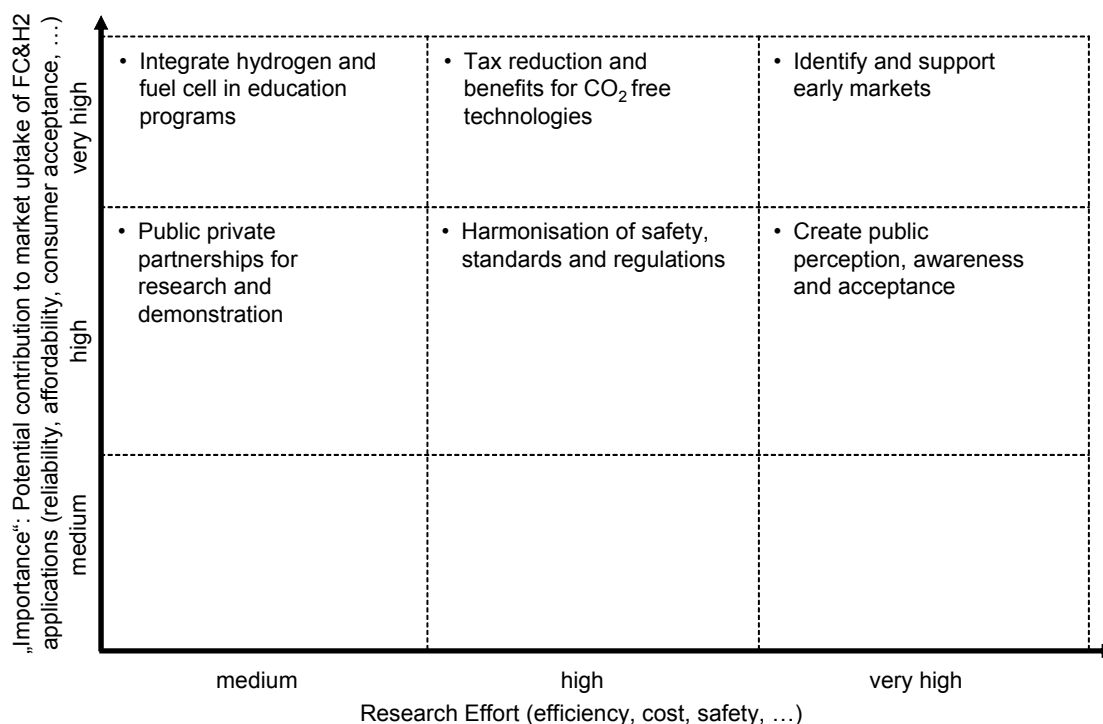


Figure 8.6: Prioritization Matrix for Cross-cutting issues [8.8]

These issues, and associated policy conclusions, are discussed in much greater depth in the next chapter. In overview, the research agenda needs to consider the following:

- At the academic end of the scale, there is a continuing need to understand what drives early markets, and feed that learning into the key actors in the public-private partnerships that may supply or support them. Increased and sustained use of public procurement programmes is a likely need, so public actors need access to reliable information on what such programmes can offer
- Moving towards early and then mass-markets, the issue of “internalising externalities” is recognised if not always supported by policy. Fiscal incentives and taxation schemes that recognise full socio-economic costs must be constructed and promoted to support early and niche markets, and research needs to provide the information to construct such schemes correctly
- Public perception and acceptance can be promoted by demonstration projects and education (at all levels) about the benefits of a CO₂ free energy cycle with hydrogen, as well as detail skilling of the engineering and servicing workforce. Such initiatives are a central task for public-private partnerships, as is the international harmonisation of standards for safety, component specifications (refuelling couplers, standardised parts, etc.) and regulations for installation or use



8.4.5 Concluding remarks on research priorities

At overview level, a few key themes emerge from these priorities:

- Ensuring a seamless “pipeline” of new technology from basic research into product applications, in areas where progress is required to increase the attractiveness of Fuel Cells and Hydrogen. Key needs addressed by this pipeline are the reduction of costs and improvement of robustness / durability. This pipeline can only thrive if support mechanisms address the needs of each actor, recognising in particular the challenges faced by small, innovative enterprises with disruptive technologies
- Realising the scale-up of both fuel and application production, such that low cost and consistent good quality is realised in mass-manufacture. This enterprise needs of course to be industrially led, but with support from the science base to understand and solve key technical challenges, and with stable policy environments from Government to ensure that long-term investments can be made with confidence
- Ensuring that the correct package of fiscal incentives, regulations, codes and standards are in place to remove “unreasonable” obstacles and ensure a level playing-field of cost that accounts for items today considered “externalities” (especially environmental and social issues). In its broadest context this is a great challenge (requiring, for example, the re-consideration of free-trade agreements) – the implication for researchers is that these issues need to be fully understood



9. Conclusions for Primary Energy and Hydrogen Infrastructure

9.1 Why Fuel Cells and Hydrogen are relevant to Energy Policy

It has not been a primary project objective to create recommendations for European energy policy. Nonetheless, the project's findings have highlighted three important issues that need to be addressed at energy policy level:

- **Applications that use hydrogen as a fuel, require a de-carbonised hydrogen supply** in order to realise their full environmental potential – with existing hydrogen energy chains, these applications may not be competitive with other future options in terms of energy-chain greenhouse gas emissions
- **Renewable and low carbon energy policy needs to provide for hydrogen manufacture** in order to realise this de-carbonised supply of hydrogen fuel; therefore policy for the ramp-up of wind and other renewable energy, nuclear power and carbon capture technologies needs to provide a surplus above the needs of grid electricity generation alone
- **Interactions with the electricity grid need to be considered in future policy:** in particular, the possibility to use hydrogen manufacture from electricity as a reversible energy buffer, and the impact of fuel-cell based distributed heat-power systems on grid control

9.2 Medium term infrastructure build-up

The project has shown how promotion from civic authorities can play a significant role in the early stages of market uptake for Fuel Cell and Hydrogen products, by leveraging public funding, finding synergy with civic needs for improved mobility and air quality, and creating a critical mass for purchasing (Chapters 6 and 10). This civic market can create clusters of infrastructure, in terms of both fuel distribution and maintenance expertise; from these clusters, fuelling infrastructure for non-captive fleets can spread out, mainly along trunk routes (especially if private hydrogen vehicles have short-range electric capability [4.15]). This fuel infrastructure will, at least initially, be supplied by an extension in the output of existing industrial sources. The following are important points to consider for policies that might support this:

- The industrial hydrogen industry derives its profitability from efficient utilisation of assets: so stakeholders from this sector need to be highly engaged in build-up plans to prevent imbalances of supply and demand giving rise to disruptively high hydrogen prices
- Incentives need to encourage distribution to be environmentally efficient, in terms of energy used for compression, liquefaction and haulage



- Longer term energy and carbon trading policy needs to encourage a non-disruptive transition to more de-carbonised hydrogen, at a sufficiently early stage that mainstream adopters are using a low carbon energy chain and delivering genuine environmental benefits

9.3 Long term Energy requirements for making Hydrogen as a Fuel

According to the Roads2HyCom findings summarised in Chapter 7, total European hydrogen demand in 2050 could be between 0.5 and 1.5 million GWh per year (expressed as energy in the hydrogen, not primary energy demand to make it), which is around 3-7% of current total energy use in the EU-27. Most of this hydrogen will be used in road transport, which currently accounts for over 10% of EU consumption – the decrease in share is accounted for by the superior efficiency of the Fuel Cell, and by the incomplete market penetration of hydrogen as a fuel.

The scenarios for 2050 relate to a very significant mass market for hydrogen-fuelled applications. As has been previously explained (chapters 4, 7 and 8, [4.15]), lower-carbon hydrogen is required to ensure that these applications are competitive with future benchmarks. For example, on a “well to wheels” CO₂ basis [4.15]:

- Today’s state of the art fuel cell vehicle is broadly competitive with the most efficient known fossil-fuel hybrid (combustion engine / electric) technology if it is fuelled with current industrial hydrogen
- High use of carbon capture in a fossil-based hydrogen supply would be required to make the same fuel cell vehicle competitive with an electric vehicle charged from today’s (average) European grid
- Hydrogen made from electricity that is 60% renewable would be required to achieve the same effect

If one accepts that pure electric vehicles are likely to continue to offer limited driving range, and that significant substitution of fossil fuel is desired by 2050, then these levels of de-carbonisation of the hydrogen supply must be catered for in future energy policy. As described in Chapter 5, there is a potential for around 50 to 100 thousand GWh p.a. in 2030, which equates to around 8-12% of the “mature market” demand for 2050 - so it is broadly consistent with where a de-carbonised supply needs to be in 2030, if it can be realised in practise. It is therefore vital that energy policy relating to wind energy development, grid load management and relevant fiscal incentives allow this to happen.

Naturally there may be concern in the energy sector, that Hydrogen is “unproven” as a mass-market fuel and therefore projected uptake may be inaccurate; however, the supporting technologies required from the energy sector (carbon capture, renewables and other low carbon sources such as nuclear) are of generic usefulness in meeting the future environmental objectives of that sector.

Furthermore, it should be noted (as described in Chapter 5) that either high taxation of conventional transport fuels, or a stronger emphasis on energy security (meaning reduced reliance on imports) might favour the diversion of further low-carbon energy toward hydrogen production.



9.4 Interactions with the Electricity grid

The final area in which energy policy needs to recognise the arrival of Fuel Cells and Hydrogen, is the transformation of energy networks, particularly the electricity grid, to a distributed model with appropriate mechanisms for power flow control and trading (Chapter 5). However, this issue is again a generic one: Even without Fuel Cell and Hydrogen technologies, the advent of generation de-regulation, other distributed power technologies, and the storage potential of electric vehicle batteries connected to the grid, all drive a similar policy need. By recognising this issue in policy, the uptake of Fuel Cells, Hydrogen and other environmentally efficient technologies can be encouraged.



10. Conclusions for the Community and Policy-making

10.1 Why civic initiatives and government policy will remain important

Fuel Cells and Hydrogen face the same classic conundrum as many other sustainable energy technologies in most sectors of application. The potential for long-term societal benefit may be great; but in the short-term, products are likely to appear as costly alternatives in markets with mature incumbent technologies, and buyers (both private and commercial) with a cautious approach to risk and long term investment. Going forward there remains a clear role for civic authorities (municipalities and regions) and governments (member state or at European or other federal level):

- **To promote early-adopter projects** with a high profile in terms of the public or commercial decision-makers, that establish the credentials of products and energy chains that use the new technologies
- **To use public procurement** to create larger early markets, and start the process of realising economies of scale that can lead to more widespread adoption
- **To put in place policies that encourage the adoption** of new products and their energy chains, and remove barriers that may have unintentionally arisen

In many cases, such measures can be technology-neutral (meaning that the incentive prescribes a desired impact, not a specific solution), meaning that synergy can be realised with other sustainability initiatives (renewable and lower-carbon energy supply, efficient and low-emission products). In other cases, more technology-specific policies may be desired; it is important to fit the policy measure to the individual situation.

10.2 How Roads2HyCom has engaged with Communities and developed Policy recommendations

Following on from the socio-economic landscaping described in Chapter 6, the project has engaged in a number of work elements to develop a range of social initiatives, from high level policy recommendations to detail engagement at community project level:

- **Creation of a set of three Handbooks** to guide the development of community-based projects [10.1, 10.2, 10.3]
- **Co-operation with the HyLights coordination action** [3.2], which focuses on Hydrogen for Transport demonstrations and has launched the H2Moves.eu initiative [10.4]



- Participation in the establishment of the **Hydrogen Regions and Municipalities Partnership** (HyRaMP, [3.7])
- **Organisation of three Workshops** with community stakeholders and in partnership with HyRaMP [3.7], at which material from the Handbooks, the HyLights [3.2] and HyWays [3.3] projects, and stakeholder experiences were presented and discussed [10.5]
- **Two presentations to the European Investment Bank** in support of their development of new Risk Sharing Finance Fund instruments [10.6, 10.7]; and creation of specific recommendations for financing and business development [10.8]
- **Clustering analysis of selected regions**, based on information gathered in chapter 6, to develop conclusions regarding future regional growth potential [10.9]
- **Study of existing policies of relevance**, and development of policy recommendations [10.9, 10.10]

10.3 Establishing Fuel Cell and Hydrogen communities

The analysis described in Chapter 6 [6.5, 6.6] highlights some important conclusions regarding the establishment of community-based projects, namely:

- **The importance of establishing and sustaining political will**, and the policy and fiscal support derived from it
- **The importance of recognising local factors**, whether they be needs that might drive the project, or legacies of resources, infrastructures or capabilities that might enable it
- **The importance of reproducibility**, by outward expansion or connectivity to similar initiatives, in evolving the project into a self-sustaining or growing market for Fuel Cell and Hydrogen based products and services

Recent developments such as the creation of HyRaMP [3.7] indicate a strong and growing desire at European municipal and regional level, to take a pro-active approach. It is therefore important that those who are becoming pro-active, receive the right advice so that they can structure initiatives that are effective. With this objective in mind, the Roads2HyCom project has created a series of three Handbooks [10.1, 10.2, 10.3]. Key messages from these Handbooks include the following:

- **Understand the technology** – what it can (and cannot) do in terms of issues like air quality, greenhouse gases and energy security – and use this understanding to reach an informed decision about whether Fuel Cell and Hydrogen technologies are the right choice (as an example, both London and Hamburg cities are procuring hydrogen buses, but only in small quantities –



the majority of their fleets are being replaced with the more pragmatic Diesel-Hybrid technology)

- **Understand the vision** – putting the project into the context of European energy policy, so that long term objectives can be correctly established (as an example, short term hydrogen supply may be industrially based, whereas long term vision may migrate this supply to an identified de-carbonised source)
- **Understand your strengths** – using the assessment framework developed by Roads2HyCom [6.6] to characterise the local situation and understand what this means in terms of likely success
- **Understand the benefits** – not just in terms of environmental issues, but also the promotion of local businesses or of the public image of bus services, municipal power utilities and other stakeholders
- **Get the detail right** – not overlooking issues such as public acceptance and planning regulations which can cause a well intentioned project to go sour
- **Learn from experience** – in respect of issues like those mentioned above, and the broader technical and logistical challenges of the project – there is now a wealth of such experience available to learn from
- **Be realistic in expectations** – especially regarding the degree of support that industrial stakeholders will be willing to provide where the technology is at prototype level: in many cases, rising demand for prototype devices cannot be met by manufacturers at a price that is reasonable, and the multiplication of risk from release of incompletely validated technology is seen as unacceptable
- **Plan properly** – covering all the phases of the venture, and using past learning to capture everything that needs to be embedded in a robust plan
- **Promote the project** – to ensure sustained political will and public acceptance of this type of initiative as a necessary role for civic authorities
- **Have a good exit strategy** – with the objective of developing the project into something that is self-sustaining in a context of prevailing future policies and technology advances; it is particularly important to ensure that subsidy funding can be sustained to the point where the initiative starts to become “bankable” or self-sustaining (financing is covered in the section below)

Transport is often a key element of community initiatives, especially in cities where the promotion of accessible local public transport is an important part of the civic authority's role. For this reason the HyLights project, a co-ordination action supported by the European Commission, major road vehicle manufacturers and fuel suppliers, was created especially to address this field [3.2]. HyLights has created comprehensive guidelines and project assessment frameworks for such projects, and coordinated the efforts of stakeholders in developing future plans. HyLights has also



created the “H2Moves.eu” initiative [10.4] to promote ongoing collaboration between transport projects and promotion to the public.

10.4 The role of Finance in Community projects

Funding and Finance have enormous importance to the gestation of any innovative new industry: failure of financial mechanisms can lead to “valley of death” phenomena whereby innovation that is approaching market readiness can falter in the face of insufficient market pull and competition from incumbent products. The right financial mechanisms can create conditions whereby new products can be brought to market in a commercially robust manner.

Roads2HyCom has highlighted financial issues in several parts of its studies – for example, Chapter 4 highlighted a divide between small and large enterprises, high grant dependency, low levels of “bankable” investment, and only a small proportion of players investing at true pre-commercialisation levels; Chapter 6 highlighted funding as a key challenge for community projects.

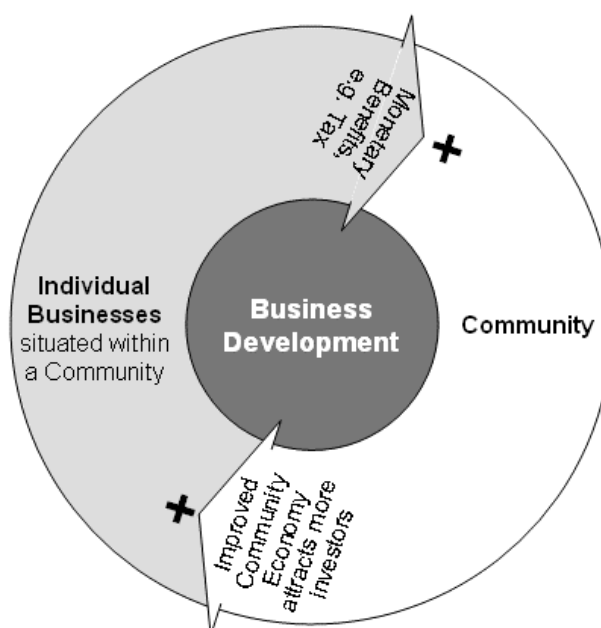


Figure 10.1: Virtuous circle of community business development [10.8]

The development of Fuel Cell and Hydrogen related businesses within a community, has various impacts on the overall state of the community, as business accomplishments create certain overall benefits for the community which in turn increases the attractiveness of this community for other investors. For example, the success of businesses developing the new technology is likely to require the



participation of local university research facilities; in turn, the capabilities of local universities will improve, increasing the possibility of receiving research funding and R&D awards, which in turn enhances local reputation and experience. Another local monetary circle is the creation of new jobs, and thus the increase in overall consumer capacity to buy products, which in the long-term may foster overall regional economic growth.

Such is the importance of issues such as these to the development of extended community projects (beyond the scale of today's demonstrations), that the project participated in two presentations to the European Investment Bank in support of their development of new Risk Sharing Finance Fund instruments [10.6, 10.7]; and has created a set of specific recommendations for financing and business development of community projects [10.8].

All businesses require some element of seed funding, but the purposes for which it is required vary depending on the source of the business concept. Overall, the access to capital at early stages of market development is a crucial issue for the small, innovative businesses that play a significant role in the landscape of European technology development (Chapter 4). This has remained a difficult issue for small-and-medium sized companies in Europe, especially in comparison to the USA [10.7]. Recent developments however indicate that better financing options are available and that those options need to be considered in Fuel Cell and Hydrogen development, both for civic projects and for small-medium enterprises – and also for larger businesses.

The Higher Risk Sharing Finance Facility (HRSFF) is a financing mechanism provided by the European Investment Bank, which intends to facilitate loan access and aims at leveraging research, technical development, demonstration and innovation investments from private entities owing to the catalytic effect that a project awarded an EIB loan is likely to generate. Overall, the new scheme allows the EIB to become involved in more risky projects and enables an increase in financing volume issued by the EIB. Access to the risk sharing finance facility can take two different routes. One route is through participation in a FP7 project, which automatically qualifies for the EIB Financial evaluation. The other route to an EIB Financial evaluation is via participation in other European Projects. Ideas which pass the EIB Financial Evaluation are evaluated again according to “bankability”, or the ability of the project to develop revenues sufficient to sustain and re-pay debts. Those RTD projects that prove themselves to be bankable, can receive an EIB Loan. The significance of this is enormous, especially for smaller businesses that have previously struggled to co-fund Framework research and to fund the non-grant-eligible product development that follows it.

The RSFF scheme includes mechanisms whereby interest rates are related to commercial sector success, thus de-risking the investment in promising but unproven technology – the debt must be re-paid, but the mechanism provides a bridge across the “valley of death”. Another important feature of RSFF is that it includes mechanisms to facilitate the financing of Projects by means of Project finance. Traditionally, financing uses Corporate Financing Models (financing of a recognised commercial entity) – but establishing a Community project with such a model can be challenging because of the diverse nature of the project's stakeholders. As yet, no Fuel Cell or Hydrogen community project has developed a case for “bankability” or



accessed these mechanisms; it is to be hoped that the just-started JTI is the first step in bringing this prospect nearer.



Figure 10.2: Corporate and Project RSFF mechanisms [10.6]

10.5 Clustering at Regional level, and conclusions for Reproducibility

As community-based projects move from being essentially demonstrations (a very limited number of products used in a visible way) to being larger, more self-sustaining and more self-replicating, it becomes important to understand the conditions under which this might happen. This part of the study [10.9] has therefore developed a methodology of Cluster Quotients, which has been employed to study the relationship between current geographical clustering of Fuel Cell and Hydrogen activity, and that of other areas of commercial activity. Along with a geographically based review of other data from the project, this analysis has been used to develop conclusions for policy relating to the development of clusters.

Some key findings were:

- **Regions that are very active in pursuing Fuel Cell and Hydrogen deployment are typically also very innovative regions.** This finding is consistent with endogenous growth theories and thus confirms the hypothesis that innovative regions can more easily engage with and advance these technologies
- **The most active regions in the field are characterized by the location of industry clusters** that might be logically closely linked to Fuel Cells and Hydrogen. This correlation is particularly strong for clusters in chemical products, power generation and production technology. The over-average importance of these industries in early adopting regions reflects the early stage of Fuel Cell and Hydrogen market development. The relative importance of industries that provide end-use applications (such as transportation) is likely to increase in a later stage of the technologies' market development.
- The correlation between early adopting Fuel Cell and Hydrogen regions and existing hydrogen production capacities as well as pipeline infrastructure is weak. Small projects can indeed be done with on-site hydrogen production or



shipments of gaseous or liquid fuel (Chapter 5) and do not require existing production or pipeline infrastructure - the latter should therefore not be seen as preconditions for a project

- **Less innovative regions**, whose participation will eventually be required as enlarged community projects make the transition to a more general market, may therefore need tailor-made support schemes to help them engage with Fuel Cells and Hydrogen. However, it may seem reasonable that such support should be subject to the condition that the less innovative region in question possesses some other success factors (e.g. hydrogen production infrastructure) which promise to make the investment a rewarding one.

These points can help to develop a comparative assessment scheme and support ensuing policies. The Hydrogen Regions and Municipalities Partnership (HyRaMP, [3.7]) may be in a good position for coordinating efforts and developing tools for benchmarking across regions and across differing technologies. With growing development of Fuel Cell and Hydrogen activities and clusters, these tools should be refined and causal relations for success should be investigated as soon as data for time series analyses are available.

Table 10.1: Cluster Quotient

| Cluster Category | CQ |
|--|-----|
| Medical Devices | 4,7 |
| Publishing | 4,4 |
| Distribution service | 4,3 |
| Analytical Instruments | 3,9 |
| IT | 3,9 |
| Biopharmaceuticals | 3,1 |
| Power generation and transmission | 3,1 |
| Chemicals | 3,1 |
| Sporting | 2,9 |
| Production Tech. | 2,9 |
| Aerospace | 2,9 |
| Communications equipment | 2,9 |
| Forest products | 2,8 |
| Lighting | 2,8 |
| Plastics | 2,7 |
| Entertainment | 2,4 |
| Jewellery | 2,4 |
| Oil and Gas | 2,4 |
| Automotive | 2,4 |

| Cluster Category | CQ |
|------------------------|-----|
| Business Services | 2,1 |
| Building Fixtures | 2,0 |
| Constr. Materials | 2,0 |
| <i>Tobacco</i> | 1,9 |
| <i>Education</i> | 1,6 |
| <i>Leather</i> | 1,5 |
| Heavy Machinery | 1,4 |
| <i>Finance</i> | 1,4 |
| <i>Agricultural</i> | 1,4 |
| <i>Textiles</i> | 1,3 |
| Transportation | 1,3 |
| <i>Fishing</i> | 1,3 |
| <i>Hospitality</i> | 1,2 |
| <i>Metal manufact.</i> | 1,1 |
| <i>Footwear</i> | 0,9 |
| <i>Apparel</i> | 0,8 |
| <i>Furniture</i> | 0,7 |
| <i>Food</i> | 0,7 |
| <i>Construction</i> | 0,7 |



10.6 Conclusions for Policy

10.6.1 Observations on European policies

The screening of existing EU policies [10.9] unfolds some inconsistencies in the macro-framework for the promotion of Fuel Cells and Hydrogen. The EU is strongly committed to reduce GHG as shown by its role in the Kyoto Protocol framework and the Council conclusions. Fuel Cells and Hydrogen are conceived as an instrument to reduce GHG. The EU therefore strongly supports research and development in this field through its Framework Programmes. However, the EU policy framework for the promotion of Hydrogen as a fuel is not as strong and coherent as its commitment to these technologies may suggest. Key issues observed are:

- **The EU lacks a clear mid to long term strategy** explaining the desired role of different energy sources and carriers. In view of avoiding lock-in effects, this absence of technological preferences is understandable. Since this is under responsibility of member states, the EU could use the Lisbon method to develop a coherent strategy together with Member States, which also embraces policy for the long term ramp-up of carbon-free energy sources from which to make hydrogen.
- **Changes in EU policies must closely be analyzed** with regard to their effects on hydrogen and fuel cell development. Examples include Taxation of Hydrogen as a fuel in some member states, and the impact of Emissions Trading Schemes - exemptions would assist a transitional phase, but need to be linked to the ramp-up of zero carbon hydrogen production so that hydrogen production is not seen to enjoy "unfair advantage" beyond a managed transition period.
- **The EU lacks competences** necessary to reach its ambitious energy policy goals - the Treaty of Lisbon would give the EU level stronger legal competences in the field of energy, but other matters of relevance for energy and climate change policy will remain at national level such as taxation. Stronger coordination of national policies is therefore needed.
- **The overall policy framework** must be aligned with the challenges ahead - otherwise, different policies might neutralize each other, for example improvements in energy efficiency and the liberalisation of the electricity and gas markets may for instance reduce the share of energy expenses in household or corporate budgets, leading in turn to higher energy consumption (because it is affordable) - hence, not only a coherent policy framework is needed but also a clear link between the energy objectives of GHG reduction targets, deployment and roadmaps on the one hand and instruments on the other.

The following are key elements for a potential policy framework for Fuel Cell and Hydrogen promotion:

- **Develop long term GHG reduction targets** in line with other EU energy objectives and the hydrogen deployment strategy at EU level



- **Maintain taxation on energy** with a view to internalize externalities, while revising taxation on Hydrogen consistent with the “supply greening” issue described above
- **Incentives** to comply with the targets of the first point above can be market based - instruments may be combined:
 - **Feed-in systems** for producers of Fuel Cells and Hydrogen
 - **Permits** for early adopters / purchasers of Hydrogen vehicles
 - **Dynamic standard setting** and visible label (and monitoring) of full life cycle carbon emissions for energy-intensive products including vehicles
- **A Pan-European network of agencies** for energy efficiency to coordinate efforts (analogy to European Energy Regulatory Agencies)
- **Financing SMEs** in the Fuel Cell and Hydrogen area (as described above)
- **Regional funding:** cluster policy (as described in the next sections)

10.6.2 Regional Policy

Policies for promoting regional industrial clusters have, in recent years, been adopted by many regional authorities in Europe, as well as by Member States and the European Commission. Successful policies for the promotion of clusters should be based on measures tailored to the specific needs of a particular region. However, some general elements can be identified:

- **Support to formulating a vision and strategic aim** amongst stakeholders (private companies, research institutes, consumer groups, etc.), which are likely to be interested in the development of a cluster
- **Catalytic role:** Promotion of networks among companies, research institutes and regionally based interest groupings, with the aim of multiplying the number of collaborations between different organizations within the same community, while also embracing external linkages and access for new entrants
- **Public procurement policies** for stimulation of regional markets and brands for innovative products
- **Facilitation of administrative procedures**, by reducing the administrative burden on innovation activities, in order to facilitate their implementation
- **Establishment of regional research and innovation centres** on sustainable energy (including fuel cells and hydrogen) with the aim of speeding up the transfer from academia to demonstration and implementation as well as developing research driven clusters of global excellence



- **Support advocacy coalitions** that can strengthen the social acceptance of the technology (legitimacy) e.g. through demonstrating new applications
- **Facilitation of access to financing** and giving seed money

Modern cluster policies also emphasize the need for a good coordination of policies at both EU, national and regional levels, since they foster joint action between different stakeholders.

Both cluster analysis and policy analysis suggests not to favour certain technology choices (“picking out the winners”) - the range of feasible applications and attractive technologies will become wider the more the technology advances. In fact, variety should be seen as desirable since it increases competition as well as technological and business options.

10.6.3 European policy and the cooperation of Regions

Based on information and feedback received so far it is very likely that there will be a variety of different regional strategies in Europe. The European level should hereby play a coordinating and enabling role:

- **The EU should ensure the guidance of the innovation process** by setting goals and developing visions that can legitimize and empower coalitions strong enough to threaten incumbent technologies. Such guidance should be developed in cooperation with a range of public, private and non governmental organizations to ensure consensus and create visibility and acceptance of the course
- **The EU should use its coordinating role** to try to ensure that the different technological options are fully covered in one or more regions - Given the unpredictability of future technological and market developments, Europe has an interest in being well positioned in different emerging markets
- **The EU should harmonize regulatory processes**, standards and certification processes not only for production and product-related applications but also for infrastructure and distribution (e.g. fuelling stations); furthermore, it should ensure that Member States apply the mutual recognition principle, which “guarantees free movement of goods and services without the need to harmonise Member States' national legislation”
- **Pioneering regional clusters should exchange information**, best practices and group together for certain activities such as **joint procurement**

The grouping and cooperation of regions at EU level (such as in HyRaMP, [3.7]) is of great importance, as once regions have grouped together they can gradually become more and more interconnected. Thus common action can yield manifold benefits:

- **Joint procurement:** a group of regions can purchase certain products together; the supplier may thus realize economies of scale whereas the regional purchasers will get a lower price for the demanded product



- **Producer-user networks:** If a producer supplies a relatively great number of regions with the same product, they will benefit from the feedback of users in different communities and geographical settings, while the regional users of the product can also benefit from such a network for they can exchange information on how to best deal with technical problems or combine the product with other applications
- **Interconnected infrastructure:** Regions and emerging Community projects will have an interest in connecting their hydrogen infrastructure with those of other regions nearby. As the number of fuelling station and the length of pipelines grow, the geographic range of vehicles will increase and the supply of hydrogen will be diversified. The more these early adopting communities become interconnected, the more applications as such will become attractive

Besides its role as coordinator, the European Union can also play the role of a financial facilitator. Alongside the Framework instruments that are well known to Technology developers, and the EIB finance schemes described above, it will in due course become of great importance to geographically enlarge the hydrogen infrastructure in Europe, in particular in view of facilitating the uptake of hydrogen as a fuel in road transport. The EU may therefore set up a programme designed as private public partnership to connect regional networks such as the emerging Scandinavian one – the appropriate timeframe for action possibly being towards the end of the just started Joint Technology Initiative. The EU funding for the partnership could for example partly be covered by the Trans-European-Transport-Networks (TEN-T) budget as well as by structural funds.

10.6.4 Specific policies to incentivise uptake

Because of the sustainability dimension, public policy is legitimate to foster such cluster development and to stimulate lead markets. In considering this dimension, linkage needs to be made to the long-term “greening” of the hydrogen supply (because current manufacture of hydrogen, like electricity, gives rise to GHG and other emissions at the point of production), but provided that support policy is clearly linked to the greening of hydrogen as a fuel, effective mechanisms could include, e.g. via:

- **Congestion charges and zero emission zones:** The introduction of a congestion charge in London shows that this can well be done at community level. If low or zero emission vehicles are granted privileged access to cities, the overall effect will be favourable for uptake in the community
- **Parking lot management:** Zero or low carbon emitting vehicles could be granted free access to parking lots - This is also a measure which can be implemented at regional level
- **Tax exemptions:** Hydrogen producers could be granted exemptions from energy taxes, which would improve the relative cost competitiveness of hydrogen relative to fossil fuels
- **Housing policies:** Fuel cells for stationary use can be supported by national or regional housing policies, e.g. via information campaigns, financial support or tax exemptions for energy efficient products



- **Public purchasing:** Public administrations can choose to purchase “green” products to support their market development
- **RTD funds for sustainable energy:** These funds could partly be financed through energy taxation revenues or carbon permit auctioning - Examples for such funds can already be found at regional level e.g. in Hanover [10.9]

After the completion of the just-starting Joint Technology Initiative, which has a life of ten years, regional/civic initiatives and community projects will have to “find their own ways” towards commercialisation. In this respect, regional infrastructure and cluster policy, and access to suitable finance, will be of paramount importance. Further ongoing research is, however, needed to learn more about the regional dimension and to better prepare and support European regions on their way towards the realisation of Fuel Cells and Hydrogen in a sustainable energy economy.

10.7 Broader application to early adopters of Sustainable Energy

As a final note, it is worth pointing out that most of what has been learned in the context of civic-society issues (municipal early adopters Fuel Cells and Hydrogen, government policy), may be equally applicable in other Sustainable Energy fields, which may well co-exist with Fuel Cells and Hydrogen in the future. Common factors include:

- **The use of new technology** that is not yet available at a sustainable free-market cost, is not well understood by users, but nonetheless could possess an attractive environmental image
- **The use of new energy vectors** that are not yet widely available or supported by infrastructure
- **The need for coordinated intervention** to promote a critical mass of uptake for the purpose of learning and as a step to more commonplace usage

Fields such as biomass/biofuels, electric or plug-in hybrid vehicles, and local renewable power generation could all possibly benefit from using this knowledge and sharing their own experiences with early adopters of Fuel Cells and Hydrogen.



11. Conclusions for Education, Training and Skills

11.1 Introduction, and the Roads2HyCom approach

Skills shortages are a common feature of the technology landscape when a new technology starts to become successful. These shortages can stretch right across the value chain, from applied research and product engineering, to manufacturing and maintenance. It is important to ensure that a lack of skills does not become a barrier in the Fuel Cells and Hydrogen arena.

Roads2HyCom has focused on education and training in the engineering sector, because European economic development policy is generally focused on the “high value” parts of the value chain. In the early stages of technology uptake, this is where skills shortages are at risk of occurring: graduate education in engineering is a process of at least 4 years, often 6; and the engineering sector is where skills will be required to overcome the technical challenges described in the previous chapters.

The project assembled a small team of academic members, led by a premier engineering university, to develop modules for graduate and postgraduate engineering training [11.1]:

- **High-level training** (bachelor or master degree) is aimed at trainee engineers, with an emphasis on education for Fuel Cell and Hydrogen technologies implementation and/or research
- **A more specific, minimized course** is proposed for fast updating of knowledge for life-long training of graduated engineers at master level
- **A smaller module** is suggested as a component for more general courses

11.2 The Roads2HyCom Education Agenda

The proposed courses [11.1] have been structured for inclusion in Master or Bachelor study Engineering courses, and include:

- **A high level of explanation** of the current technological challenges, and visions to bridge these gaps in future
- **A practice-driven approach** reconstituting real-life professional situations through case studies and practical examples
- **Time space for workshops** with individual or group projects

Summer or weekend courses of life-long education are proposed, including:

- **Truly tailored compact courses** designed for high-level executives from the private sector and participants of summer schools



- **Time space for workshops** with individual or group projects

Figure 11.1 illustrates the main building blocks of the curricula above. The Roads2HyCom team has also identified **some critical success factors** for education in Fuel Cells and Hydrogen:

- **The quality of lecturers is important** – efforts should be made to ensure that those with real industrial or research experience are attracted to lecturing posts
- **The curriculum needs to be flexible**, so that it can be adapted to the needs of both vehicle/transport and power engineering domains, using a modular structure with multiple use of newly developed or tailored current subjects
- **The curriculum on the other hand needs to have sufficient breadth** to develop understanding of the complex interaction of Fuel Cells and Hydrogen with the broader Energy economy

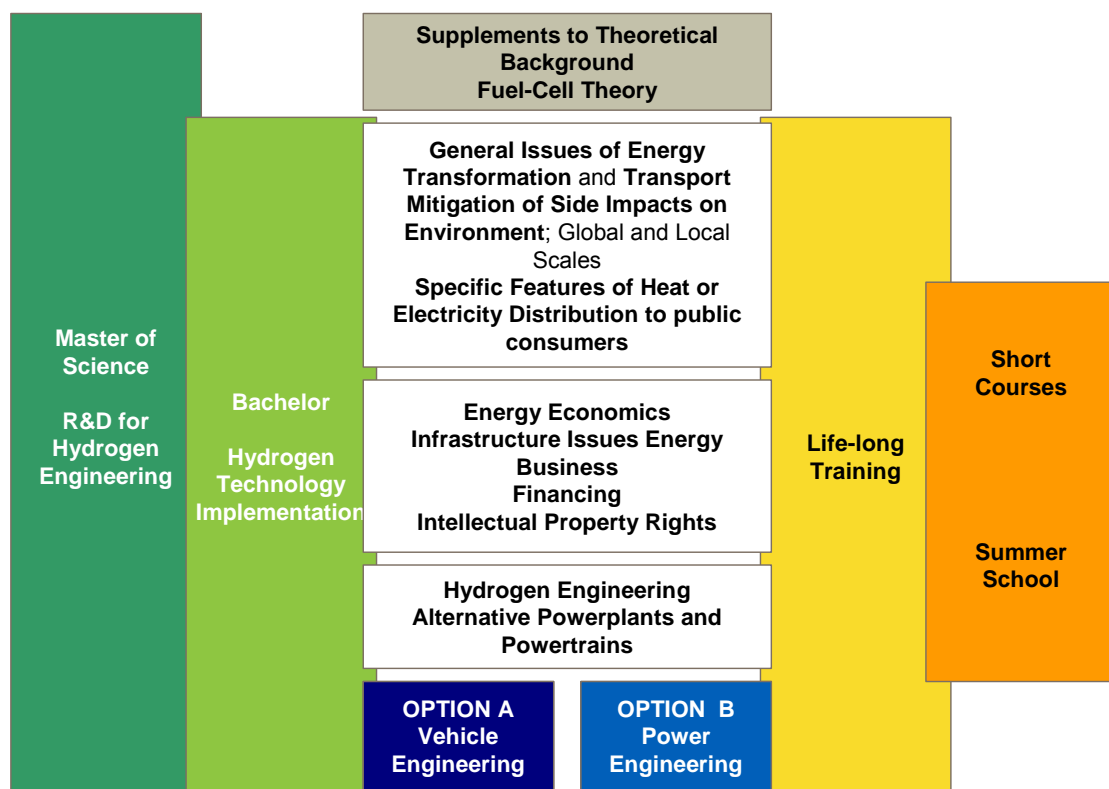


Figure 11.1: Building blocks of the proposed curriculum [11.1]



12. Concluding remarks

Fuel Cells and Hydrogen constitute a very broad topic in terms of the diversity of technological detail and socio-economic backdrop across the range of energy chains and applications. It is therefore impossible to draw simple, universally correct conclusions at summary level. In fact it is important to acknowledge the complexity of the field, in terms of the diversity of applications and technology solutions, the complex linkage to energy supply and the electricity grid, and the potential for government policy to have an influence on future direction.

There have been many “false dawns” in the Fuel Cell and Hydrogen sector, perhaps due to the eagerness of researchers and politicians alike to find solutions to the very pressing challenges of energy security and climate change. However, Roads2HyCom has found evidence of genuine, significant developments. Noting the risk of stating a generalisation, it can be said that:

- **The technological state of the art is advancing significantly**, but the right support and incentives (in particular, for research and technology development) are still very much required to address critical issues such as the **storage of hydrogen** in vehicles, real-world **fuel cell durability** (including impurity tolerance), and the realisation of cost-effective higher volume **manufacture**. For critical issues such as these, mechanisms that foster the development of **technology pipelines** from basic research to the industrial sector, encourage collaboration, and constantly monitor progress of the State of the Art, will be required
- **There will be an increasing need to develop the engineering, manufacturing and servicing skill-base**, as more Fuel Cell and Hydrogen technologies approach the point of commercialisation, in order to support their arrival in the market – a strong position here is essential to support Europe’s **high value position** in the global economy
- **There are significant early markets** created by specialised application niches whose nature (often high asset utilisation or the requirement to provide electric energy more effectively than a battery) creates a “**business case**”; and by the **political will** of municipal early adopters. These markets need to be encouraged to grow and replicate by implementing appropriate policies at European level. Required policies include harmonisation of standards, incentives to encourage early markets, and ongoing measures to unite the efforts and share the experiences of early adopters
- **However, in the most mass-produced applications such as transport, civic initiatives alone cannot generate enough product volume** to bring down costs to profitable mass-production levels, even in a high crude oil price scenario. This means that the final step needs to be taken by the manufacturer, in bringing forward early halo-products that (as was the case with Hybrid vehicles from the late 1990s) attract early adopters but are not profitable for at least a decade. Therefore, **government policy to support fiscal incentives and infrastructure build-up must be consistent over**



that period (and sound in terms of environmental and energy security credentials) to ensure that manufacturers have the confidence to take that step

- **There is a critical need to link the development of sustainable and low carbon energy policy, to that for the supply of hydrogen** as a fuel, so that the environmental potential of hydrogen-fuelled applications can be realised; the linkage to grid development and sustainable electricity (which both complements and competes with hydrogen as an energy vector) is especially critical
- **Europe appears to hold a reasonable position** in respect of these issues, with technology applicable across a range of sectors, appropriate technical skills and potential for adaptable, multi-level (European, National, Regional) political support. It is inevitable that Europe will need to bring in technologies and energy resources from overseas; equally, Europe should be in a strong position to deliver **high value exports**. Efforts to promote more cohesion need to be **flexible**, and focus on Europe's strengths

To reflect these conclusions in a way that indicates what needs to be done now, the project has proposed seven "success factors" for Fuel Cells and Hydrogen:

| Roads2HyCom's seven success factors for Fuel Cells and Hydrogen in a Sustainable Energy Economy |
|---|
| Vigorous research to address key issues – Realisation of mass-production, durability and impurity tolerance, Hydrogen storage in vehicles |
| Development of the Skill-base – Research, product engineering, manufacturing, servicing |
| Stimulation of early markets – Fiscal incentives, Civic procurement, removal of bureaucratic barriers, sharing of learning |
| Financing – Availability of research and infrastructure grants, venture capital and business loans, on a suitable, stable and secure basis |
| Stability of long term policy – Sustained policy support, financing and incentives to promote industrial investment in mass production |
| Joined-up Energy Policy – Clarity of priorities (environment, energy security), Availability of low-carbon energy, integration with a smarter electricity grid |
| Flexible European Cohesion – Playing to our strengths in international markets |

- **Vigorous research to address key issues:** Vigorous research remains very necessary to support first markets and bring the technologies into new ones. The project has shown how the State of the Art is progressing, and highlighted how much further it must ultimately go. Realisation of products and processes for low cost mass-production, improved durability and impurity tolerance, and hydrogen storage in vehicles were common themes. But the



research agenda must remain dynamic and responsive to technology breakthroughs and market shifts

- **Development of the skill-base:** As the new technologies permeate the market, skills will be needed to get them there and keep them there. The project has highlighted markets where Fuel Cells and/or Hydrogen are reaching first markets now, and postulated others for the future. Skills for these markets need to cover the research pipeline, product design & development, installation, servicing and repair. Outreach of re-skilling needs to be broad: for example, many small organisations service domestic heating and private vehicles. As a first step, a flexible education agenda has been developed to serve this transition at technologist level
- **Stimulation of early markets:** The success of early markets is vital to promote trust in these new technologies. The project has looked at technical, regulatory, fiscal and social issues; and characterised some key civic markets. There are no showstoppers in these early markets – but the detail has to be got right. Fiscal incentives, political agendas and removal of bureaucratic barriers are all important elements. The project has developed topic studies on acceptance, safety, financing and early products; and Handbooks for civic initiatives
- **Financing:** Financing is an important topic poorly understood by technologists: without it, getting to a sustainable market is difficult. A majority of stakeholders, from technology developers to civic projects, are highly grant-dependent and cite lack of funds as a key barrier. Small, innovative players often struggle to access finance in the way that large, stable corporations can. Changes of thinking, from capital cost to total ownership & environmental cost, are necessary to promote uptake; Subsidies and fiscal incentives that “internalise the externalities” will be necessary for some time. But ultimately, the sector must transition to a “bankable investment” that repays debt and provides return on equity
- **Stability of long-term policy:** Committed, stable policy is vital – sustainability is not often a “quick hit”. Many stakeholders, including product manufacturers, fuel suppliers and application users, will only be able to justify their investments on a long-term basis. Policies that encourage them to do so must show corresponding stability and commitment: fashion-driven policymaking could deter investors. Commitment to research funding, fiscal incentives and “internalising the externalities” will be necessary for some time. The transition TO a fossil-fuel economy, from the first use of steam power to drain mineshafts in the early 18th century, to the last use of sailing ships to bring grain to Europe in the 1930s, took 200 years. Despite pressing need, the transition to sustainability will be no shorter
- **Joined-up Energy Policy:** Fuel Cells and Hydrogen must be considered in the wider energy context. The project has shown how a realisable, clean hydrogen supply depends on cohesive thinking on the ramp-up of sustainable energy and the re-shaping of the electricity grid. Creation of a publically accessible hydrogen fuel infrastructure requires investment – investors will want to see a cohesive, robust long-term policy that avoids “nasty surprises”.



Even for the simpler case of fuel cells that use fossil fuels, joined-up thinking is needed to ensure that the business case can be forecast reliably

- **Flexible European Cohesion:** Europe is strong because it combines regional differences with a common purpose, allowing cases of best practise to flourish and be copied (and improved upon). The project has shown how Europe's 27 member states and more than 250 regions each has unique needs and capacities, albeit with some significant common threads that allow such best practise to be replicated. In coming together to address the sustainability challenge, Europe's actors need to recognise strength in this diversity, not control their efforts to a uniform template. There will be successes and failures – if Europe's approach is flexible but cohesive, we will magnify the successes

Over the lifetime of the Roads2HyCom project, unprecedented peaks in the price of fossil fuels and increasing political concern over environmental issues have significantly strengthened the case for many clean energy technologies. Echoing trends observed in nature, the future is likely to be one of increasing diversity of energy supply and use, as each new source or technology finds niches to which it is best adapted. In a scenario of constrained fossil fuel supply and greenhouse gas emission, a strengthened market for efficient devices like the fuel cell, and clean fuels like "green" hydrogen, is inevitable. The challenge now for Europe is to bring together critical masses of stakeholders in technology development, energy supply and the wider community in order to ensure that the vision of Fuel Cells and Hydrogen in a sustainable energy economy is realised.



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Further information on the project and on Fuel Cells and Hydrogen is available on the project's website, www.roads2hy.com



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